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CONTENTS

1. CAD/CAM applications in polymer processing:
A review of flow simulation methods

2. Design analysis and optimization of moulded products in CAD/CAM environment

3. Design analysis and simulation of injection moulds

4. Simulation of moulding shrinkage on a CAD/CAM system

5. Programmable controllers in an integrated moulding system

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CAD/CAM APPLICATIONS IN POLYMER PROCESSING: A REVIEW OF FLOW SIMULATION METHODS

BY

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1. INTRODUCTION

In today's world, plastics have penetrated nearly every market conceivable. They are light weight, durable and inexpensive. These characteristics combined with their ease of processing have led to a sharp increase in the demand for plastics products.

The primary function of the processing operation is to impart the desired shape to the finished product and may involve moulding, extrusion, coating, thermoforming or other processing methods.

Plastics processing implies that the material is subject to a varied thermo-mechanical history in order to transform the polymeric raw material experienced by the material contributes to the microstructure which is developed in the finished part and consequently determines the ultimate properties of the product. The rheological behaviour of the materials therefore plays a critical role for the development of a proper understanding of polymer processing technology (see figure 1).

The highly competitive nature of the industry has created the need for the automation and control of polymer processing operations in order to enhance process productivity and product quality. A key aspect of this technology is the development of computer aided design/manufacturing (CAD/CAM) software packages.

The objective of this paper is to review and discuss the aspects of CAD/CAM technology related to the mathematical representation of flow simulation. A review of the techniques and key phenomena involved in the simulation of polymer processes such as: injection moulding, blow moulding, extrusion, film blowing, wire coating and calendering will be made.

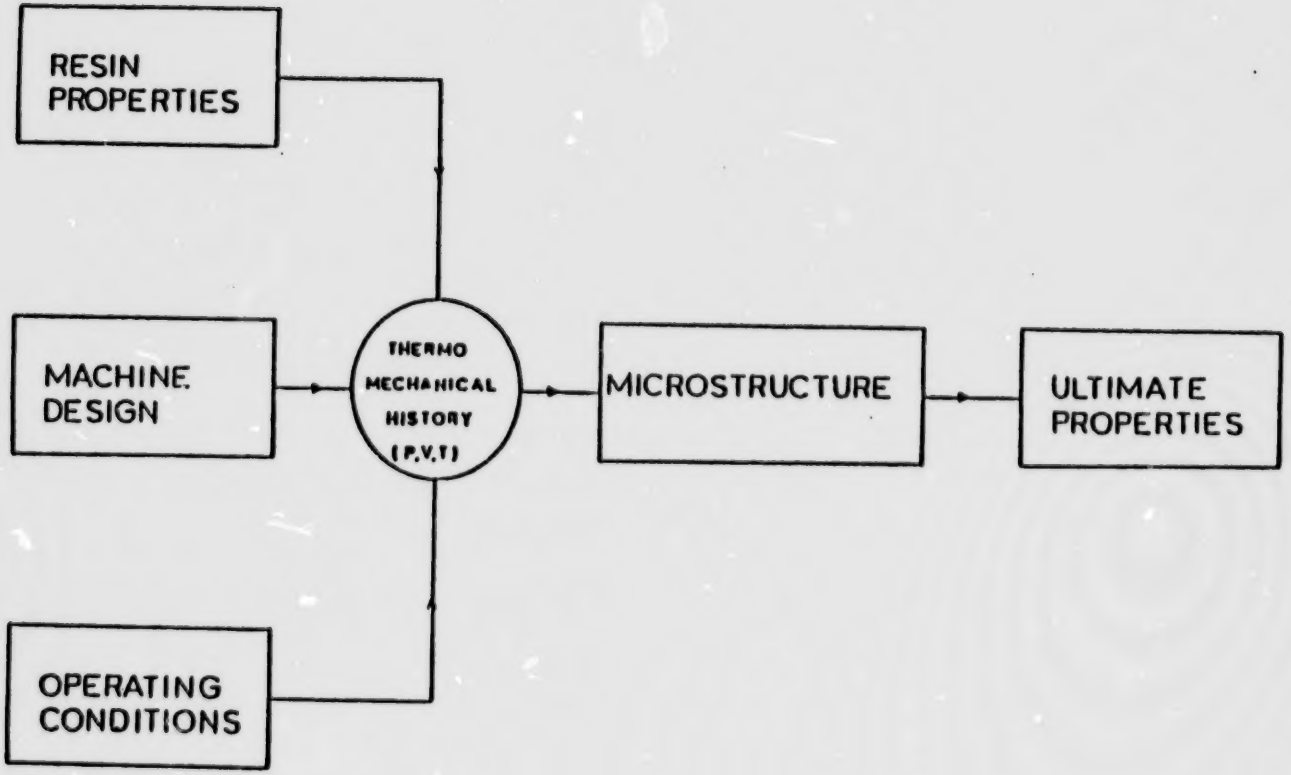


FIGURE 1 : Components of the Plastics Processing System.

2. PLASTICS PROCESSING [1-5]

Plastics processing generally involves the transformation of a solid resin, usually in the form of pellets or powder, into a final product with a specific shape, dimensions and properties. This transformation may be viewed as a multi-step process involving: solids transport, heating, melting, mixing, melt conveying, shaping, cooling, and finishing. It should be mentioned that several of these operations may occur simultaneously (see figure 2).

Plastics processing operations can be classified into two general categories as follows:

a) Primary Forming Process

b) Secondary Forming Process

The primary forming processes can in turn be subdivided according to the dimensional control of the shaping step.

Two dimensional operations include sheet, pipe and profile extrusion, film blowing, fiber spinning, wire coating, calendering, etc. These processes are generally continuous operations.

Three dimensional operations include compression, injection and blow moulding. These processes are generally intermittent or cyclic operations.

The secondary forming processes involve the treating of a product previously formed in a primary process in order to further change its shape, appearance or improve its properties. Among these operations we can cite: thermoforming, embossing, hot/cold rolling, ultrasonic welding, plating and decorating.

The processing of plastic materials is characterized by complex interactions between the material, process configuration (i.e. mould and die design), and processing conditions. These interactions ultimately determine the mouldability of the material, the economics of the process and the properties of the finished product. It is therefore essential to develop a unified approach or theory which incorporates a model of the material, processing operation and product. This "integrated approach" underlies many of the CAD/CAM systems that are under development in conjuction with polymer processing.

3. PROCESS SIMULATION

The last decade has witnessed a remarkable change in every facet of the computer industry. The most significant changes have been in the area of computer hardware, that is the actual electronic components associated with data processing, information storage and display technology. A case in point is the infusion of computer aids to the mechanical design industry. The ability to routinely construct and display models of three dimensional objects, and then transform this information to instructions that drive the fabricating machinery has a tremendous impact on the productivity and even the professional activities of engineers.

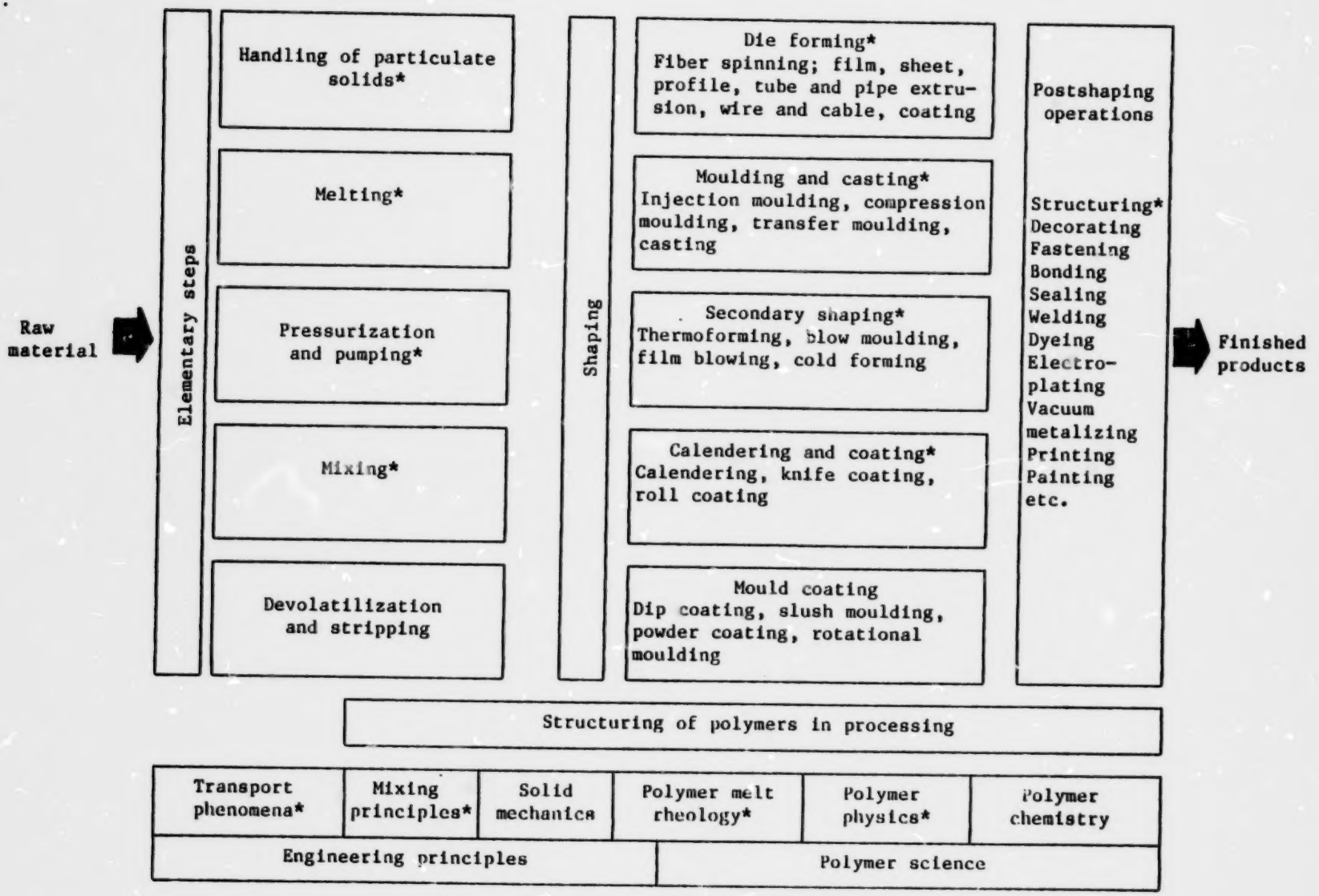


Figure 2: Polymer Processing Classification

To distinguish between the CAD/CAM technology of the mechanical design industry and the broader aspects of computer usage in engineering design the term Computer Aided Engineering (CAE) is used. To illustrate the difference, consider that CAD systems for mould design deal primarily with the fabrication of the mould, while CAE attempts to describe the moulded article. That is to say, CAE must incorporate a full description of the moulding process, since the final properries of the moulded article reflect the resin's entire experience from hopper to ejection from the mould. This goal is achieved through the development of computer simulations of the different plastics processes.

Computer simulation is a tool that has been employed in research applications to extend the scope of an analysis beyond that readily obtainable through experimentation. In general, computer simulations deal with two main aspects, i.e. mathematical model of the process and numerical techniques employed to find and display the solution. A schematic representation of the modeling philosophy is given in figure 3.

3.1 Mathematical Modeling [6-9]

The mathematical analysis of polymer processing operations involves the solution of the equations of conservation of mass, momentum and energy. Table 1 gives the tensorial representation of these principles.

The equation of conservation of momentum, also called equation of motion represents the balance between the kinematic (velocity field) and dynamic variables (pressure and stress fields) acting on any given fluid. Due to the vector and tensor characteristics of the velocity and stress fields the equation of motion has three components and involves nine unknowns. Therefore, it is necessary to introduce an expression that relates the velocity and stress fields. This relationship, called the constitutive equation, is used as the defining equation for specific types of material behaviour under flow, i.e. newtonian, purely viscous non-newtonian, viscoelastic, etc.

The equation of conservation of energy represents the balance of the heat transfer to and from the system due to convection, conduction, viscous dissipation, phase change, etc.

In order to solve a particular problem it is also necessary to specify a set of initial and boundary conditions. These are the mathematical representation of the "real" problem to be solved.

In general, polymer processing operations involve the flow of complex fluids in non trivial geometries. An attempt to solve, analytical or numerically, the complete set of conservation equations and boundary conditions becomes a monumental task. Therefore, in many cases assumptions and approximations are employed. These considerations have to be established after a careful analysis of the phenomena occurring in the real problem and their validity will determine the success or failure of the proposed model.

A general classification of the assumptions most commonly used in simplifying the conservation equations is given below.

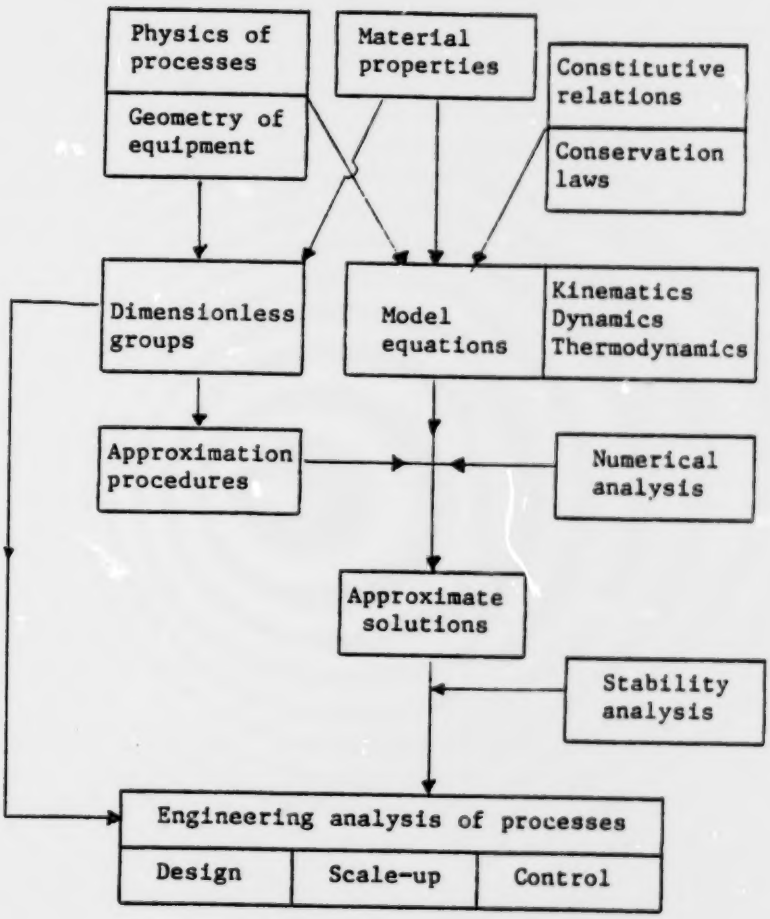


Figure 3: Modeling Philosophy

Table 1: General Tensorial Form of the Transport Equations.

Continuity: $$\frac{D\rho}{Dt} = -\left(\underline{\nabla}\cdot\rho\underline{v}\right)$$

Momentum: $$\rho\frac{D\underline{v}}{Dt} = -\underline{\nabla}p - \left[\underline{\nabla}\cdot\underline{\underline{\tau}}\right] + \rho\underline{g}$$

Energy: $$\rho C_p\frac{DT}{Dt} = -\left(\underline{\nabla}\cdot\underline{q}\right) + T\left(\frac{\partial p}{\partial T}\right)_\rho \underline{\nabla}\cdot\underline{v} - \left(\underline{\underline{\tau}} : \underline{\nabla}\underline{v}\right)$$

Level 0: No assumptions.

Level 1: Assumptions related to the material properties: rheological constitutive equation, equation of state, specific heat and thermal conductivity.

Level 2: Assumptions related to the forces acting on the system: inertial, viscous and body (gravitational) forces.

Level 3: Assumptions related to thermal forces: conductive, convective and viscous.

Level 4: Assumptions related to the time effects: steady or unsteady state.

Level 5: Assumptions related to the dimensionality of the problem.

Finally, and in the context of polymer processing simulation one can distinguish two classes of mathematical models:

a) Mouldability models supply information regarding the thermo-mechanical history (temperature, pressure, strains, deformations, velocity profiles, etc.) experienced by the resin during processing.

b) Product quality models extend the analysis to obtain information regarding the microstructure (distributions of crystallinity, morphology, orientation, frozen stresses, shrinkage, etc.) of the final part.

Mouldability and product quality models are inter-related since it is necessary to have information regarding the thermomechanical history in order to predict the microstructure and the final properties.

The majority of the mathematical models describing polymer processing operations can be classified as mouldability models. Presently the focus is to extend these models to predict product properties. This involves solving the conservation equations with fewer restrictions and therefore the complexity of the problem (equations, numerical method, etc.) as well as the computational time increase significantly.

3.1.1 Rheological Considerations [10-12]

As has been mentioned before the choice of the rheological constitutive equation is an important factor in the mathematical modeling of the flow in polymer processing operations.

The choice of a particular rheological constitutive equation should be made based on the following criteria. First, it is desirable to select an equation which has the capability of accurately describing the rheological response of the material over a broad range of deformation histories. On the other hand, since this relationship must be utilized in conjunction with the transport equations its mathematical simplicity is of prime concern. Also in this context, it is important to bear in mind the characterization problems that are involved in the experimental determination of the rheological

parameters or material functions associated with the constitutive equation.

Depending on the particular process configuration the deformation may be dominated by shear or extension or may involve a combination of both. Shear dominated flows are frequently associated with flows in closed channels or cavities, whereas extensional flows often accompany free surface deformations. Furthermore, the relative importance of the elasticity of the fluid as compared to its purely viscous nature is a function of the flow kinematics. Consequently it should not be common practice to always insist on using the most complex constitutive model for all purposes; it merely needs to be adequate for the purpose at hand.

Table 2 presents a list (in increasing order of complexity) of some of the most widely used constitutive equations. They are classified as to their predicting ability for different flow situations. The categories will be denoted by the letters NA (not applicable), P (poor), M (modest agreement meaning the sign and trend of the results are correct), G (good, meaning that the data are fitted within 20%) and VG (very good).

3.1.2 Computational Aspects [13-14]

The resulting system of non linear partial differential equations in most cases can only be solved using numerical techniques. The two most common numerical schemes are finite difference and finite element methods.

Finite difference techniques are applicable to systems with simple geometries. They provide a discrete solution at specified grid points. These methods are limited to the use of uniformly sized grids.

Finite element techniques are more versatile in that they are independent of the geometry of the system and that their mesh generation techniques are semiautomatic and therefore less time consuming. They can handle free surface flows and are not limited to uniform sized grids.

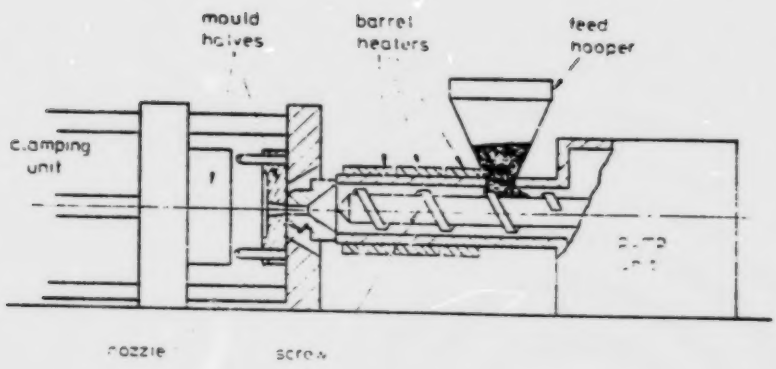
If transient and inertia terms can be neglected and if simple geometrical boundaries are involved an explicit finite difference scheme can be employed. For some transient and free surface flows a Marker and Cell technique may be used. This approach has been employed for the analysis of injection moulding in thin cavities. For unsteady flows, an implicit finite difference scheme is used owing to the time interval restrictions as a result of the usually low Reynolds numbers. Finite element methods are almost exclusively employed for the solution of free surface problems. It is common to use finite element techniques in situations involving complex geometrical shapes or contours. The finite element method has the inherent flexibility so as to achieve greater accuracy without the necessity of incurring excessive computational cost by employing a small mesh size throughout the entire region.

It should be mentioned that up to now the majority of numerical schemes used to solve accurately the problems encountered in polymer processing operations have failed in dealing with problems in which the elasticity plays a large role. Furthermore, these sophisticated schemes demand large CPU times and have to run in large main frame computers.

Table 2: Various Constitutive Relations and their Performance

Constitutive Model	Steady Viscometric: Viscous	Steady Viscometric: Elastic	Elongation: Steady	Elongation: Start/recoil	Small Strain
Newtonian $\sigma_{ij} = -P\delta_{ij} + \eta\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}\right)$	P	NA	P	NA	P
Generalized Newtonian $\sigma_{ij} = -P\delta_{ij} + 2k(II_d)^{(n-1)/2} d_{ij}$	E	NA	P	NA	P
Reiner-Rivlin $\sigma_{ij} = -P\delta_{ij} + 2\eta d_{ij} + 4\nu_2 d_{ik} d_{kj}$	E	NA	E	NA	P
Second order fluid $\underline{\underline{\sigma}} = -P\underline{\underline{I}} + \eta \underline{\underline{A}}_1 - \frac{1}{2}\nu_1 \underline{\underline{A}}_2 + (\nu_1 + \nu_2)\underline{\underline{A}}_1^2$	P	P	NA	NA	P
Criminale, Ericksen, Filbey	E	E	NA-P	NA	P
Ibid					
Linear					
Viscoelastic $\sigma_{ij} + P\delta_{ij} = \tau_{ij} = \int_{-\infty}^{t} G(t-t') A_{ij}(t') dt'$	P	NA	P	P	E
Olroyd $\sigma_{ij} + P\delta_{ij} = \eta_0 [A_{ij} + \lambda_2 A_{ij} - \mu_2 A_{ik} A_{kj} + \frac{1}{2}\alpha_2 (A_{km} A_{km})\delta_{ij}]$	M	M	P	P	M
White-Metzner $\lambda(II_d) \frac{\Delta \underline{\underline{\tau}}}{\Delta t} + \underline{\underline{\tau}} = 2\eta(II_d) \underline{\underline{d}}$	E	M	P	P	M
Bird-Carreau	E	E	P	P	E
Phan-Thien $\lambda_i \frac{\delta \underline{\underline{\tau}}}{\delta t} + Y(\underline{\underline{\tau}}, \tau)\underline{\underline{\tau}} = 2\lambda_i G_i \underline{\underline{d}}$	E	E	G	G	E
Acierno et al $\frac{1}{G_i}\tau_i + \lambda_i \frac{\Delta}{\Delta t}\left(\frac{\tau_i}{G_i}\right) = \lambda_i d_{ij}$ $G_i = G\alpha_i$; $\lambda_i = \lambda_0 \alpha_i^{1.9}$; $\frac{d\alpha_i}{dt} = \left(\frac{1-\alpha_i}{\lambda_i}\right) - \alpha_i \frac{1}{\lambda_i}\sqrt{\frac{E_i}{G_i}}$	E	E	G	M	E
KBKZ $\underline{\underline{\sigma}} = -P\underline{\underline{I}} + \int_{-\infty}^{t} \left\{ \frac{\partial U}{\partial I_{C^{-1}}} C^{-1} - \frac{\partial U}{\partial I_C} C \right\} dt'$	E	E	G	M	E
Leonov	E	G	M	M	E
Doi-Edwards Molecular theory.	M	M	M	M	M

Notes: NA = not applicable
P = poor
M = modest agreement
G = good
E = excellent



RECIPROCATING SCREW INJECTION MOULDING MACHINE

Process and Machine Variables	
Cavity pressure	Barrel temperature
Nozzle pressure	Mould temperature
Ram velocity	Hydraulic pressure
Part temperature	Injection ram back pressure
Melt temperature	Screw rotational speed
Cushion size	Shot size
	Injection and holding times

Part Qualities
Surface finish
Part density
Part dimensions
Orientation
Tensile strength
Impact strength
Optical properties
Crystallinity

Figure 4: Reciprocating Injection Moulding Machine

Table 3: Classification of Injection Moulding Studies

Level 1

Incompressible

Kamal/Kenig (momentum/energy)[16]
Kamal/Doan (momentum/energy)[17]
Kamal/Lafleur [25]
Kamal and Kuo [18]
Ryan and Chung [19]
Wang et al. [20, 21]
Harry and Parrott [22]
Broyer et al. [26]
White [23]
Lord and Williams [27]
CAD/CAM Models

Constant Thermal Properties

Kamal/Kenig
Kamal/Doan
Kamal and Kuo
Ryan and Chung
Wang et al.
Harry and Parrott
White
CAD/CAM Models

Level 2

No Inertial

Kamal/Kenig
Kamal/Doan
Kamal and Kuo
Ryan and Chung
Wang et al.
Lord and Williams
Broyer et al.
Harry and Parrott

CAD/CAM Models

No Body

Kamal/Kenig
Kamal/Doan
Kamal and Kuo
Ryan and Chung
Wang et al.
Lord and Williams
Broyer et al.
White
Kamal/Lafleur
CAD/CAM Models

No Viscous

Level 3

No Convection

Kamal and Kuo
Harry and Parrott
Wang et al. [20]
CAD/CAM Models

No Viscous

Wang et al. [20]
White
CAD/CAM Models
Broyer et al: isothermal

No Conduction

Level 4

dv/dt = 0
See No Inertial

dT/dt = 0
Lord and Williams

Level 5

1-D
Kamal/Kenig
Kamal/Doan
Stevenson [28]
Harry and Parrott
Lord and Williams
CAD/CAM Models

2-D
Kamal and Kuo
Kamal/Lafleur
Ryan and Chung
Wang et al.
Broyer et al.
White

3D

Table 3: Classification of Injection Moulding Studies (Cont'd)

Geometry

Disk	Plate/Rectangle	Cylinder	Arbitrary
Stevenson	Kamal/Doan		
Kamal/Kenig	Kamal/Lafleur		CAD/CAM Models
	Wang et al.	Lord	
CAD/CAM Models	Kamal and Kuo	CAD/CAM Models	
	Ryan and Chung		
	Broyer et al.		
	Harry and Parrott		
	White		
	CAD/CAM Models		

Constitutive Equation

Generalized Newtonian
CAD/CAM MOdels
Power law:
- Kamal/Doan
- Kamal/Denig
- Stevenson
- White
- Kamal and Kuo
- Ryan and Chung
- Wang et al. [21]
- Harry and Parrot

Polynomial:
- Broyer et al.
- Lord and Williams

Viscoelastic
Kamal/Lafleur
Wang et al. [20]

Notes:

Kamal/Lafleur: includes crystallization
Wang et al.: two models 20: viscoelastic approach
21: finite element approach
Lord and Williams: two models 27: runner and sprue system; and
cavity

4. EXAMPLES OF PROCESS MODELING

4.1 Injection Moulding [15-28]

In the injection moulding process the plastification phase is basically an extrusion operation.

The injection step involves the delivery of the polymer melt from the reservoir through the nozzle, sprue, runners and gate into the cavity. After entering the cavity the moulding cycle consists of three main steps: filling, packing and solidification (cooling). Figure 4 shows a graphical representation of a reciprocating injection moulding machine as well as the most important process, machine and product quality variables.

A complete simulation model of the injection moulding process should give a description of the behaviour of the polymer in the delivery channels and during each step of the injection moulding cycle. The analysis of the delivery channels yields valuable information regarding runner balancing, in particular for multi-gated cavities. The model should also yield information relating to both the thermo-mechanical history experienced by the material and the microstructure or ultimate properties of the injection moulded article in conjunction with cavity designs of varying geometry and complexity.

Most of the models developed up to now correspond to mouldability models or varying complexity. Table 3 presents a summary of some of the simulation models derived to describe certain aspects of the injection moulding process. This table also illustrates where the CAD/CAM oriented models are placed in comparison to the other mathematical models.

The models describing the filling phase have been fairly successful in predicting the flow front position, pressure drop, temperature distributions in the mould, position of the solid layer and even more complex phenomena such as the fountain flow effect for simple geometries. To analyze complex parts, algorithms have been proposed to piece together the results of the simpler geometries to describe any three dimensional part. This has only been done with the more simplified models. This approach has not been applied to the more sophisticated models due to the difficulties involved in establishing geometric "networks" based on the primitives and also due to the prohibitive large CPU times involved.

It also appears that the simulation results during the filling stage are not affected considerably by the choice of the rheological constitutive equation. In most cases a "power law" representation of the fluid behavior has proven to be satisfactory. In other words, the elasticity of the material appears to play a minor role when compared to that of the viscous effects.

Little research has been done regarding the modeling of the packing and solidification stages [25]. This situation is changing due to the experimental results showing the influence that this step has on the very important phenomena of dimensional stability such as shrinkage and warping.

The mathematical methods used to solve the flow of the material into the cavity range from analytical solutions, perturbation methods, finite differences and finite element numerical techniques.

Table 4: Software Packages for Injection Moulding

Name of Program	Developer or Distributor
Filling Stage	
Moldflow (2D) Moldflow Finite Element/ Graphic Package	Moldflow Australia Ltd
Cadmould (2D) Cadmould/Mefisto Plastisoft Poli-0	Institut fur Kunststoffverarbeitung (IKV) Aachen, West Germany
Optimold-Simuflow	Cornell University Graftek Inc. USA
Microplast	Cisi.Lyon, France
TMC-Flow Analysis	Plastics and Computer Inc. USA
Moldfill	Application Engineering Corp. USA
Mold Cooling	
Moldcool I & II	Application Engineering Corp. USA
Cadmould Cadmould-Isotherm	Institut fur Kunststoffverarbeitung (IKV), Aachen, West Germany
Polycool	General Electric CAE International Inc. USA
Optimold-Simucool	Graftek Inc. USA
Cooling Analysis Package	Moldflow Australia Ltd

Most of the commercial injection moulding CAD/CAM packages are based on some of the above mentioned models and deal basically with the filling and cooling stages. Table 4 gives a summary of these software packages.

4.2 Extrusion [30-33]

Solid material in the form of either granules or powder is usually gravity-fed through the hopper. After entering the helical screw channel, the polymer passes in turn through the feed, compression and metering sections of the screw. The channel is relatively deep in the feed section, the main functions of which are to convey and compact the solids. The compression section owes its name to its progressively decreasing channel depth. Melting occurs there as a result of the supply of heat from the barrel and mechanical work from the rotation of the screw. The shallow metering section, which is of constant depth, is intended to control the output of the machine, generate the necessary delivery pressure and mix the melt. On leaving the screw, the melt is forced through a perforated braker plate before flowing to the die. A schematic representation of a plasticating extruder is given in figure 5.

An extrusion die consits of a set of flow channels designed to convert the melt output from an extruder into a continuous and uniform extrudate of the desired cross-sectional shape. Most dies start with a wide distribution channel which feeds melt to the final narrow forming channels which help to meter the flow. The simplest dies are those used to make axisymmetric products such as rods. Other types are used in the production of flat film, sheet, pipe and tubular film, and in wire coating (see figure 6).

The mathematical modeling of the extrusion process includes the analysis of the phenomena of solids conveying, melting of the resin, and melt flow in the extruder. The simulation results are directly applied to the design of the key component of the extruder — the screw. The first generation models, developed in the sixties, were based on the analytical solutions of the fundamental equations of mass, heat and momentum transfer. These models were modified in order to take into account non newtonian flow behavior and effects of barrel curvature.

The next generation of models attempted to solve the defining equations subjected to less simplifications. Solution techniques based upon finite differences were used. By subdividing the extruder channel cross-section into a tiny grid, the defining differential equations could be approximated at each grid point and a consistent solution obtained. The process is repeated at intervals from the hopper to the die to get a complete picture of the melting and flow behavior in the screw. There is a clear increase in computational requirments with these techniques over the previous type. These techniques still represent the mainstream of screw analysis as well as of die design.

Over the last few years, the finite element technique has become the favorite of those engaged in the modeling of processing operations. Finite element methods are particularly useful for describing the flow in irregularly shaped regions, i.e. screws and dies, and therefore they have the potential to address problems not suitable for finite differences techniques.

It should be mentioned that the simulation models for extruders and dies demand a large amount of thermomechanical data. For example, we need informa-

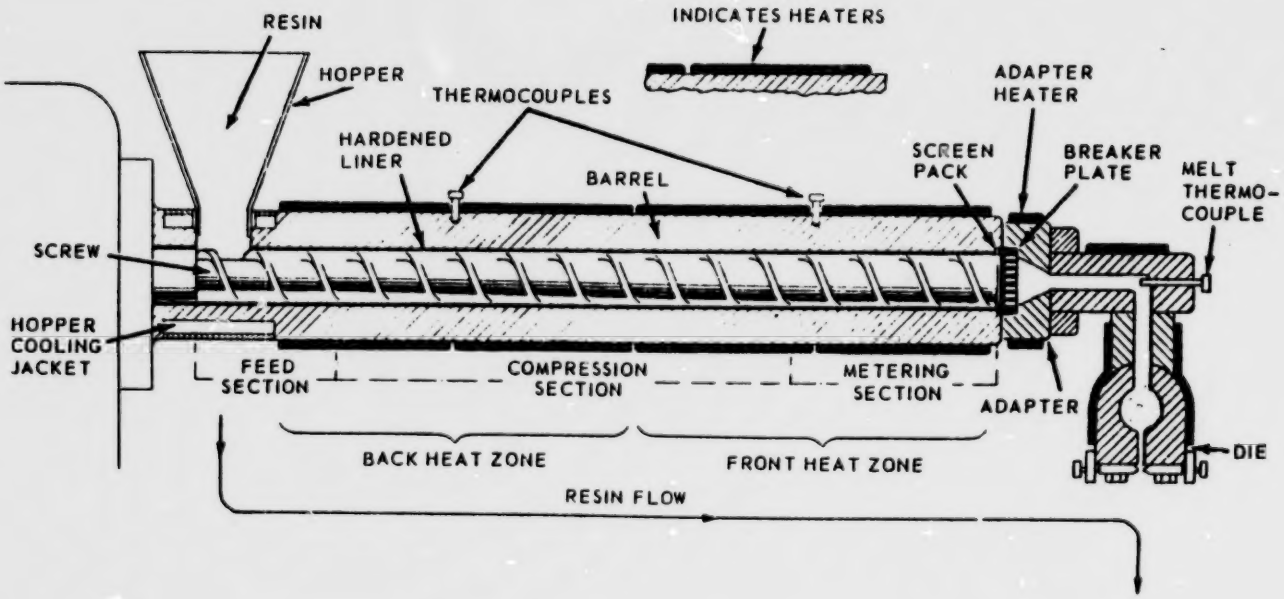
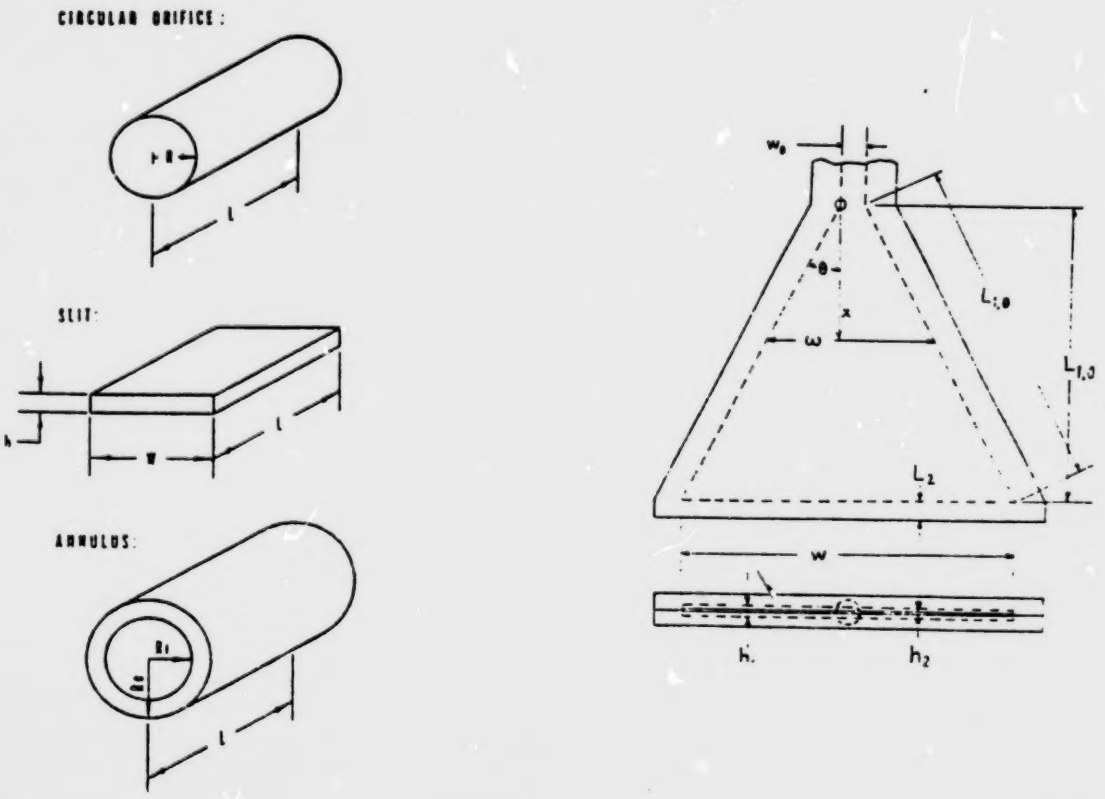


FIGURE 5. PLASTICATING EXTRUDER



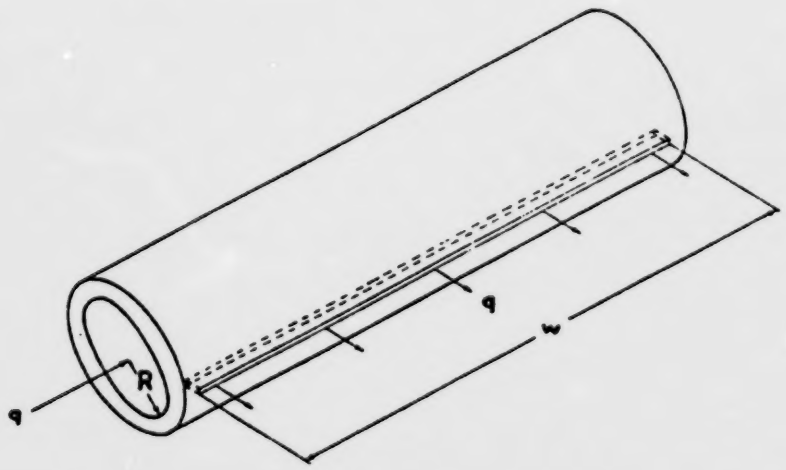


FIGURE 6. EXTRUSION DIES

tion relatd to: friction between screw, barrel and solid resin; heat of fusion of the solid polymer; viscoelastic properties for shear and extensional flows (particularly important for the design of complex dies).

4.3 Extrusion Blow Moulding [35-39]

Extrusion blow moulding is a commercially important polymer processing operation used, almost exclusively, for manufacturing hollow plastic articles. The continued popularity and importance of this process is evident from the enormous growth and diversification of the plastics container industry in recent years.

The basic extrusion blow moulding process consists of four stages:

a) a cylindrical tube of molten polymer (the parison) is extruded
b) the mould is closed on the parison, clamping it at both ends and separating it from the material still in the extrusion die
c) air is blown into the parison to inflate it and force it into contact with the mould
d) the moulded article is allowed to cool, and after sufficient time the mould is opened and the article ejected.

A schematic of the process is given in figure 7.

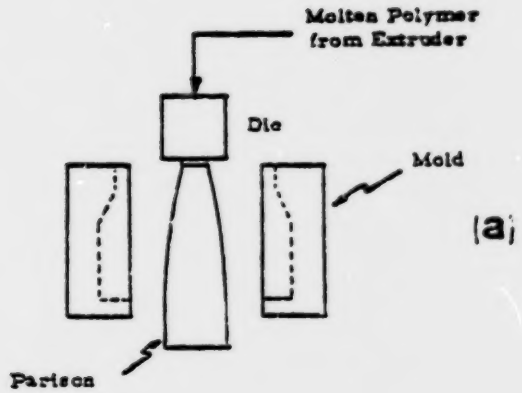
In the modeling of this process the first objective is the prediction of the wall thickness of the moulded article and in particular the wall thickness distribution along and around the article. Secondly, it is desired to relate the wall thickness predictions with die and mould design. Finally, the ultimate goal is to predict the final properties of the article using material and processing parameters.

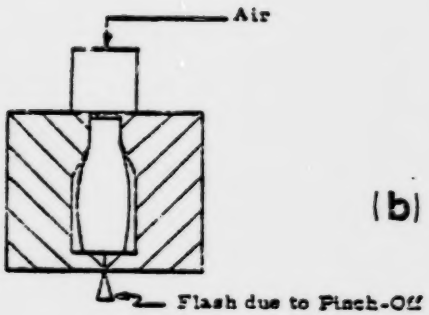
It should be mentioned that due to the complexity of this process few overall simulation models have been developed. A good review of the modeling related to the blow moulding process is given in references [35-37].

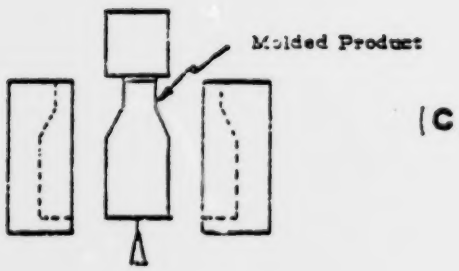
Large efforts - in the theoretical aspects as well as in the development of new numerical techniques have been devoted to predict the swelling parameters (in the absence of drawdown). However, up to now these models have been only sucessful for fluids with relatively low elasticity.

For the purpose of developing a simulation model of the extrusion blow moulding process we will describe it in terms of three distinct and sequential phases, namely, parison formation, inflation and cooling. Moreover, the inflation stage can be further divided into two distinct substages occurring in succession: free inflation, which persists until the polymer melt comes into contact with the mould surface; and confined inflation, which occurs when the melt deformation is restricted in certain directions owing to the presence of the mould walls.

The parison formation stage involves the swelling of the parison, in diameter and thickness, coupled to drawdown under its own weight. Consequently, the final parison diameter and thickness is a net result of two competing influences arising from melt elasticity and gravity. This stage is of utmost importance since it is the starting point for the other stages of the process







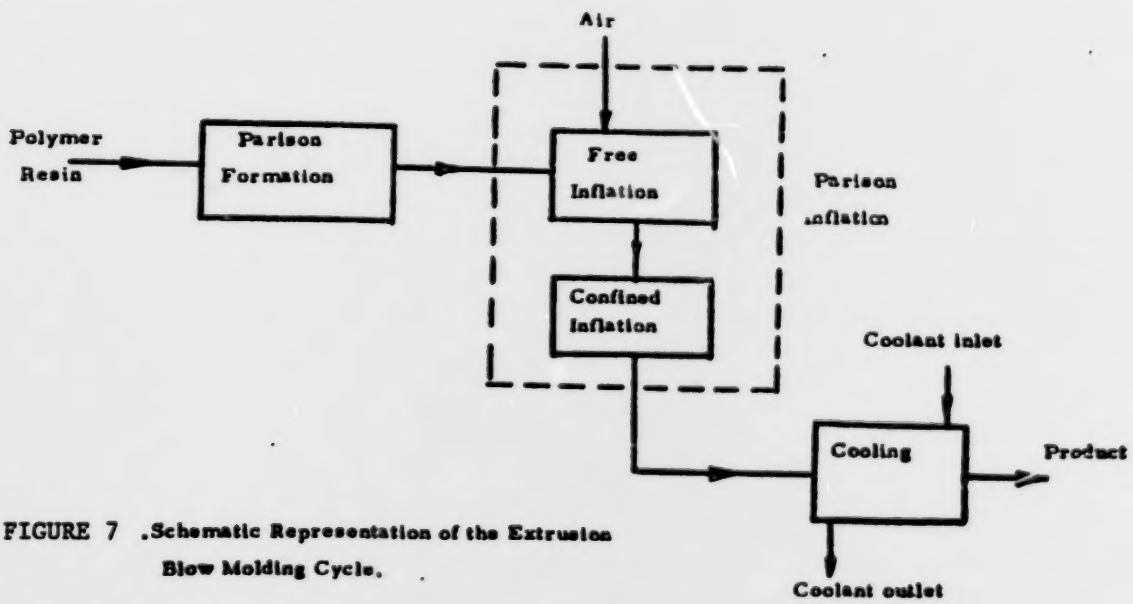


FIGURE 7 .Schematic Representation of the Extrusion Blow Molding Cycle.

and therefore will govern the wall thickness distribution of the final article.

The rheological complexity of predicting parison behavior arises from the fact that it is a free-surface problem involving time-dependent, non-isothermal elastic recovery from a complex flow of a viscoelastic fluid subject to the force of gravity.

The inflation of a viscoelastic parison involves extensional deformations. Since the process is very rapid these deformations can be quite large and the inertia of the fluid will exert a significant influence on the growth dynamics.

In the case of products of circular shape the free inflation step assumes a significant role in controlling part quality.

The confined inflation, on the other hand, is a key factor when moulding articles of non-circular shape.

In order to estimate the thickness distribution and inflation time during these stages of the process one has to assume that the deformation is isotropic; the inflation occurs under isothermal conditions; the parison at the end of the free inflation stage has a uniform wall thickness; and that upon contact with the mould surface the polymer freezes instantaneously and does not deform further. These assumptions imply that the thickness variation is governed only by the shape, size and position of the mould and the parison. The inflation time, however will be strongly dependent on the material properties of the melt.

The cooling stage, thermal design of the mould, has been traditionally modeled using a one-dimensional heat conduction approach. This hypothesis has to be reviewed since the actual phenomenon involves a combination of conduction and convection.

Both finite difference and finite element methods have been used to solve the equations governing the different stages of the blow moulding process. Reference [14] gives a very good and detailed account of the numerical techniques used in solving free-surface problems involving viscoelastic liquids. However, due to the complexity of the geometric and kinematic problems and to the need for a viscoelastic constitutive equation these methods have been applied successfully to very simplified situations; and even in these cases the computation times - on main frame computers - are rather large.

4.4 Film Blowing [40-42]

The film blowing process is based on the simultaneous stretching and inflation of a moving tube of polymer melt extruded from an annular die. The blowing "bubble" of molten polymer is cooled while this is occurring and solidifies at a "frost-line" beyond which no significant deformation takes place. The inflated circular-cylindrical tube so formed is further cooled and then passed through a train of guide plates or rollers which flatten it sufficiently for it to go through a pair of driven rubber nip-rolls. It is then wound onto cylindrical cores and sold or used as "layflat" tubing. Figure 8 gives a schematic of the film blowing process.

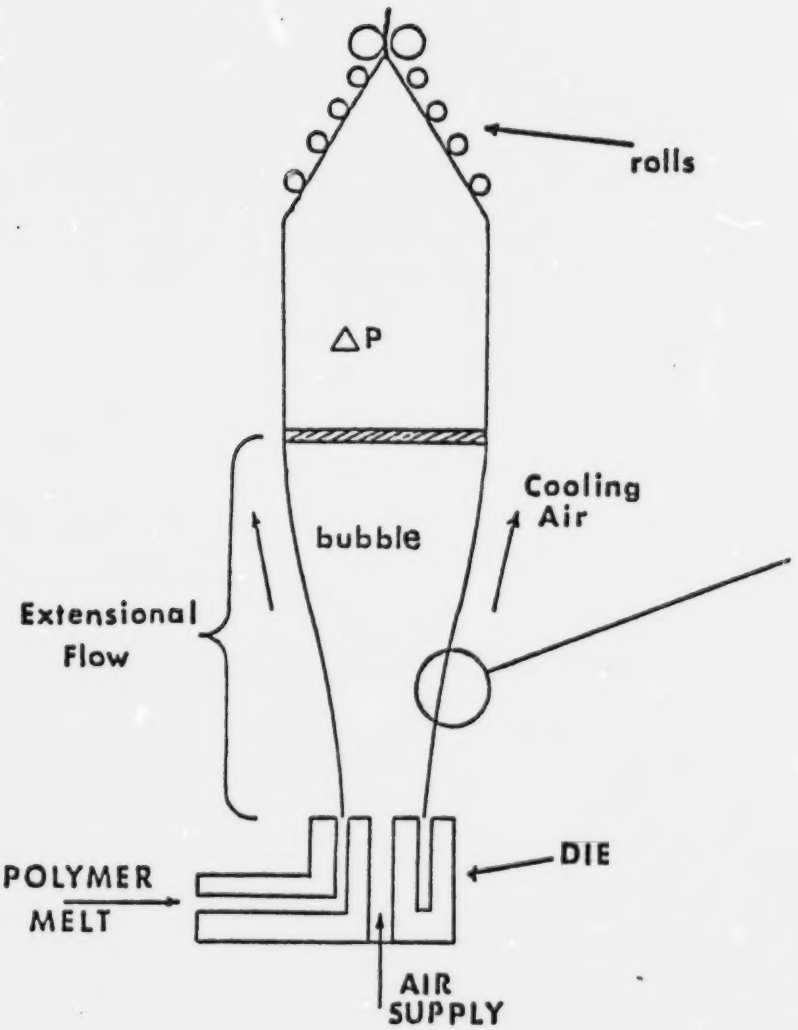


FIGURE 8. FILM BLOWING PROCESS

The two characteristic parameters of the final tubular film are the blow up ratio, which is the ratio of the final film diameter to the die diameter, and the thickness reduction, calculated as the ratio of thickness as extruded to final film thickness. Alternatively we could use the machine-direction draw ratio, defined as the ratio of take-up speed to extrudate speed at the die.

The principal goal of a mathematical simulation of the film blowing process is the development of the relationships among these geometric characteristics and operating conditions such as bubble pressure, the film speed or tension at take-up, the thermal conditions that "freeze" the film, and the rheological properties of the polymer. Furthermore, in the domain of the product quality models, it would be desirable to predict the optical and mechanical properties of the final product from material characteristics and operating conditions.

The major complication in developing a model of this system arises from the strong interaction of the heat transfer process between the film and the surrounding air with the temperature-dependent rheological properties of the melt. In addition, crystallization often occurs to a large extent, and at a rate, strongly affected by temperature and the degree of orientation of the cooling polymer. It should be emphasized that these phenomena occur superimposed on an upward free surface flow undergoing simultaneous circumferential and axial deformations.

4.5 Wire Coating [43-46]

The wire coating process can be defined as the applicaation of a specific thickness of plastic material on a moving wire. It is an extrusion operation which involves the non-isothermal flow of a non-newtonian polymer melt in a die of complex geometrical configuration. The conductor is fed into a crosshead die leading to a guider tube. As the conductor exits the guider tip, it enters the die forming region where the polymer melt coates the wire circumferentially. Two basic wire coating die configurations are employed commercially, namely, the "tube type" die design and the "pressure type" die design. In the "tube type" configuration the polymeric coating is extruded in the form of a circular tube that emerges from the die separately from the wire. The polymer is subsequently contacted or drawn onto the bare wire by virtue of its motion or by means of an applied vacuum. In the "pressure type" die the bare wire is immediately brought into contact with the pressurized molten polymer within the crosshead die. The coated wire then emerges from the die. (Figure 9).

The objectives of the mathematical simulation of the wire coating process are the development of relationships between, on one hand the operating variables and the material properties, and on the other the die design parameters, i.e. geometry, flow rate, pressure drop, etc.

Initial studies of the process have employed the lubrication approximation for cases involving tapered angles and small gaps [43]. This procedure was found not to yield clear and accurate description of the stress distribution and irregularities that might lead to flow instabilities such as melt fracture. Finite element solutions [44-46] for the two dimensional flow of an incompressible non-newtonian fluid have been developed. The isothermal new-

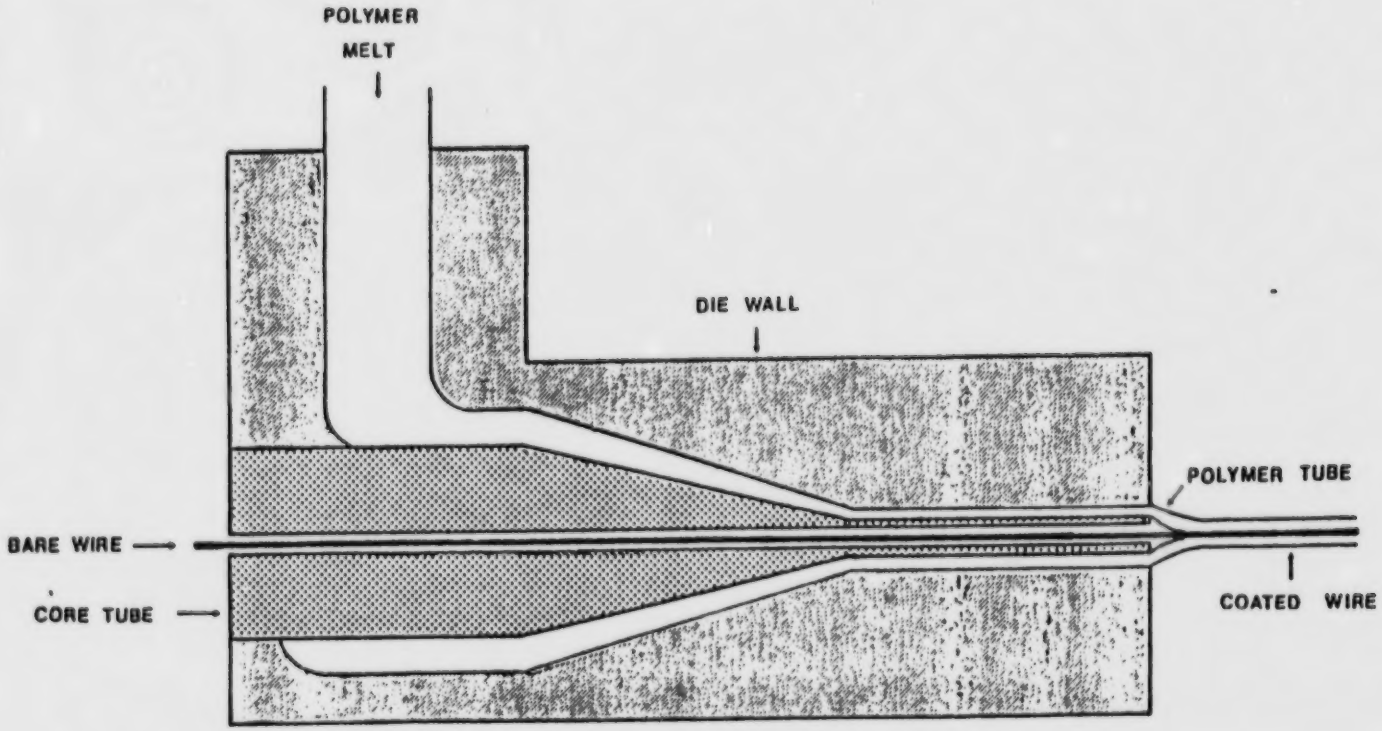


FIGURE 9. WIRE COATING DIE

tonian simulation predicted the presence of flow vortices in the area where the die changes geometry. The temperature and flow patterns are strongly dependent on the die geometry. However, when non-isothermal solutions were attempted, numerical instabilities in the temperature predictions were observed at speeds below the typical operating values.

The simulation of the wire coating process is an example of a physical situation that cannot be accurately described using simple models and approximations. However, when using more complex models the numerical techniques used to solve the equations can predict the general trends but are unable to give quantitative results within operating ranges.

4.6 Calendering [47-48]

Calendering is a continuous sheet forming operation which utilizes pairs of driven rolls and a mass of molten polymer to form a sheet of uniform thickness (Figure 10).

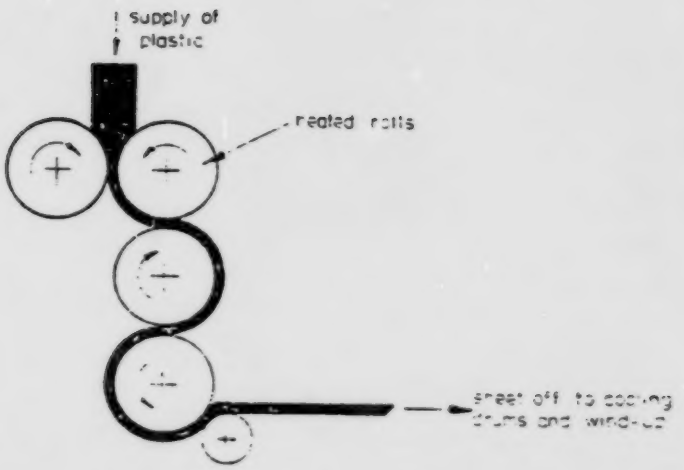
In an analysis of the calendering process one seeks the relationships among performance variables, such as sheet thickness, and design and operating variables, such as roll diameter and roll speed. Of course the effect of rheological parameters, such as viscosity and first normal stress differences, on these relationships is also sought.

The most advanced simulations have employed finite element methods to analyze the isothermal and non-isothermal 2-D calendering of newtonian and non-newtonian fluids. Results indicate that recirculating flow occurs in the entry region of the rolls, while flow becomes parallel in the vicinity of the minimum gap width. A simple constitutive equation capable of describing viscosity and first normal stress differences (elastic response in shear) has been useful in predicting vortex growth, extrudate swell and exit pressure in agreement with experimental observations.

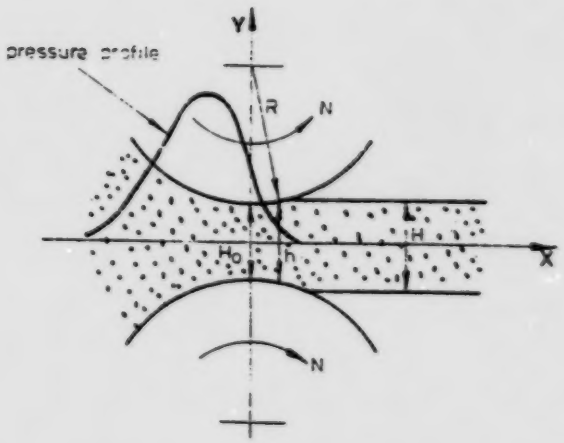
As in the case of wire coating the limitations of the simulation models for the calendering process seem to arise from a combination of constitutive equation selection, model approximations and numerical schemes used.

5. CONCLUSIONS

The mathematical modeling of polymer processing operations has progressed considerably over the past two decades. Mathematical simulations are no longer restricted to simple constitutive equations or geometrical configurations. This is partly due to the improved computational capabilities and to the further development of numerical techniques such as finite element methods. For some processes, such as injection moulding, the state of the art is quite advanced and predictions of the velocity, temperature, pressure and stress fields can be made with a high degree of accuracy. For some other processes, such as blow moulding, film blowing and wire coating, our understanding of the process dynamics is limited by the selection of the rheological constitutive equation and by numerical instabilities. Current efforts are being directed towards the understanding of the interrelationships between resin properties, processing history, microstructure development and ultimate properties.



TYPICAL ARRANGEMENT OF CALENDER ROLLS



MELT FLOW BETWEEN CALENDER ROLLS

FIGURE 10. SCHEMATIC OF THE CALENDERING PROCESS

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DESIGN ANALYSIS AND OPTIMIZATION OF MOULDED PRODUCTS IN CAD/CAM ENVIRONMENT

by

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ABSTRACT

A new conceptual approach to product design for injection moulding will be presented. Processing requirements as well as the effects of moulding parameters on product performance will be discussed.

Typical applications of a new design analysis sequence will be shown through various steps: product definition, process analysis, material behaviour, finite element modelling and evaluation of the finished product.

Realistic models will be presented and optimized interactively, taking into consideration the material characteristics and properties under service conditions. Complete finite element analysis will be performed based on the information obtained from the filling and solidification analyses. Also, problems such as weld lines, shrinkage, orientation and other geometric discontinuities will be treated during the design optimization.

INTRODUCTION

The progress in materials technology is embodied in its continuing transition from an art to an engineering science. It depends also on other technological improvements in the areas of control systems, computer graphics, heat transfer, fluid dynamics, numerical analysis, etc.

The engineering simulation of materials behaviour is the key to automation without risk. It provides solutions to avoid expensive mistakes during the product development cycle. A process simulation can describe the material behaviour under the operating conditions. This can be used to optimize product and tool design, production cycle, and material usage. Also, process simulation might answer questions about manufacturing problems or end product quality. Naturally, the engineering simulations are limited to problems that are understood well enough to be described with a mathematical modelling approach.

The research work described in this article should enlarge the technological perspective of engineering materials and stimulate their introduction into sophisticated products. A successful development of this technology will provide a competitive advantage to the Canadian industry in the following fields: automotive, aerospace, medical, electronic, construction, appliance and packaging.

BENEFITS OF AN INTEGRATED APPROACH

There is a trend towards the integration of all the design and manufacturing steps which means the ability to simulate what is going on in a process, interpret it in the design phase of products and tools and forward the same information to the production equipment. Figure 1 shows the concept of part design optimization by considering the effects of material processing and service requirements.

We must learn about the domain of application and about the product development process itself. Extensive research has been done in this field at the Industrial Materials Research Institute especially in the area of injection moulding. As shown in figure 2, the system captures the experience, knowledge and judgement of practitioners as well as the mathematical modelling of the physical changes that occur during the production and under service conditions.

A generic problem solving architecture has been designed and incorporated into the system. This decision making process is related to some concepts of acceptability. This implies the development of criteria based on engineering principles, materials sciences and general practices of sound design for manufacturing. Furthermore, a compatibility with previous decisions must be maintained. In this context, the integration means a way to effectively chain to-

gether the interrelated technologies usually involved in injection moulding, such as polymers engineering, mould design manufacturing, and material processing.

MODELLING OF PART GEOMETRY

The process begins with a tridimensional description of the object to be produced as shown in figure 3. Modelling of a part geometry implies the use of material dependent design guidelines. At this step, a computerized material information system can assist the designer in the selection of the most appropriate material. This preliminary selection can be refined later on to meet other application requirements as described in the following sections.

In order to develop a reliable model, engineers must not only have access to a system that provides the best existing value of material properties, but also the possible variation of these properties: as shown in figures 4 and 5, material properties are not fixed values but pressure, temperature, time and structure dependent. The system includes several mathematical equations governing thermal, rheological and mechanical properties [1], [2].

One can see a logical relationship between the major steps of a product development process and their associated materials databases. A parametric database has been developed from the most common design shapes by taking into account the processing requirements and material characteristics. The type and duration of loading, the temperature range, and the environmental constraints under which the product operates have to be investigated. A preliminary structural analysis can then be performed on the basis of an homogeneous material to define the minimum thickness requirements. This analysis can prevent serious design flaws and minimize the number of modifications during the next analyses.

DESIGN OPTIMIZATION BY PROCESS ANALYSIS

Mathematical models have been developed to predict how the material behaves under the processing conditions. This includes the flow simulation of the molten polymer into the mould. These models describe the melt flow pattern, pressure and temperature distributions and the melt characteristics such as viscosity, shear stress and orientation.

Figure 6 shows the flat pattern for the flow analysis as prepared from the boundary representation of the part. An equivalent representation (segmentation) of the filling pattern is developed based on the flow in the mould. The computer program evaluates the variations of pressure drop, shear stress and melt temperature along a given flow path. Possible weaknesses due to the formation of voids, weldlines and sink marks can be avoided at this stage: problem areas are highlighted for the designer which facilitates the necessary modifications for a good filling of the part [3].

Part warpage due to differential cooling rates between neighbouring regions can be minimized by reducing the level of residual stresses. Analytical programs can be used to study the heat transfer that takes place between the part and the mould during the cooling phase. Figure 7 shows the basic shapes which are supported for the calculation of the cooling cycle.

During the solidification phase, the melt characteristics vary from point to point in the mould. Since material shrinkage is not uniform in all directions, modifications of the cavity and core as well as longer set up time are required to produce parts to specifications. A computerized shrinkage analysis capability has been developed to overcome this problem. Models have been used to predict shrinkage of disks and plates under different operating conditions. A typical example is given in figure 8 for the longitudinal shrinkage which can be used during the assignment of manufacturing tolerances especially for the critical dimensions.

The expert system provides the user with the recommended processing conditions, such as melt characteristics, mould temperature, clamping tonnage, filling time and injection pressure. The designer can choose practical values to start the analysis and check if the results are within the limitations. Since the programmes are interactive, a constant feedback is given at any step and the process simulation ends when the operating conditions have been optimized.

DESIGN OPTIMIZATION BY PRODUCT PERFORMANCE ANALYSIS

Similar interactive programmes to evaluate the mechanical stresses and strains induced during the forming process are available. These programmes evaluate the effects of the clamping and ejection forces, pressure and thermal expansion on finished products. A typical application is presented in figure 9 for the design optimization of a box shaped experimental mould. These programmes can assist in the study of the following problems:

- Mechanical deflections
- Surface defects
- Crack propagation
- Flashes

The last step in the design optimization is an in depth finite element analysis incorporating the results of the previous process oriented simulations where the properties are variable, and based on the actual moulding conditions. The use of local material properties allows for the preparation of a more realistic model. This will make possible a more reliable analysis and interpretation of the results. Viscoelasticity, anisotropy, creep and fatigue behaviour can be investigated if the material properties are available in the database.

Figures 10 and 11, and Table 1 illustrate the importance of taking into account the influence of parameters such as weldlines, skin formation, temperature and humidity for an injection moulded gear in comparison with a conventional analysis. This is of prime importance for reinforced materials.

The effectiveness of this new design methodology during the optimization of another plastic part, is shown in the following example. Figure 12 shows the original model of a plastic part prior to any design optimization. The finite element model, as well as the peak stress results in the worst location are given in figures 13 and 14. Finally, by taking into consideration processing problems, the part geometry was optimized. The updated model and the corresponding peak stress results are illustrated in figures 15 and 16.

CONCLUSIONS

This article has shown new design and analysis capabilities articulated around the solid modelling technology. It incorporates procedures to address every facet of the product development cycle never before available in any CAD/CAM/CAE system. Partial solutions are not effective and achieving a good level of integration requires a good understanding of the manufacturing technologies. The implementation of this technology can improve the working procedure and streamline the flow of information during the product development cycle. Also, we have seen the advantages of using during the design phase of moulded products some interrelated technologies, such as filling and cooling simulations, finite element modelling and materials engineering.

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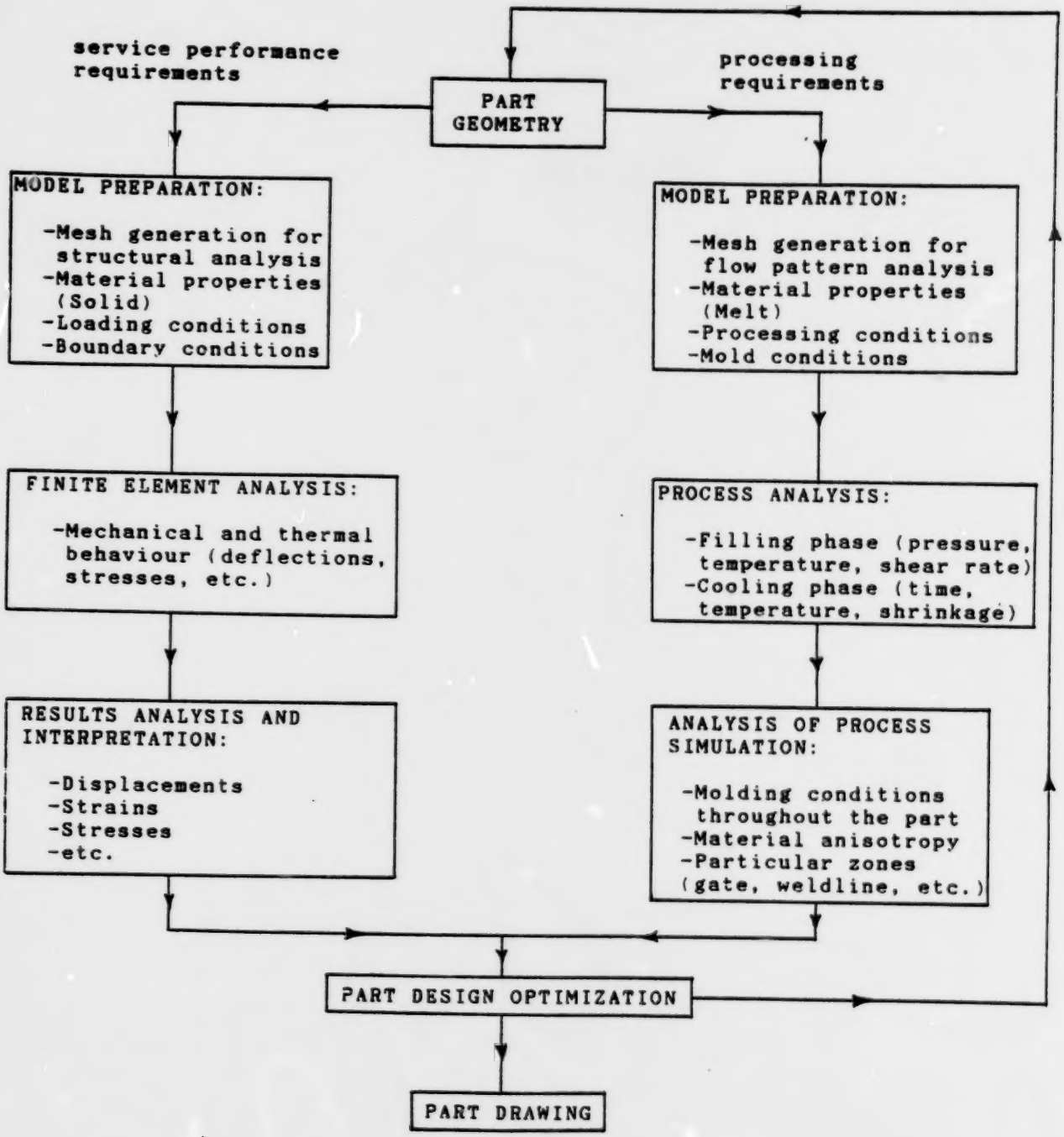


Fig.1 . PART DESIGN OPTIMIZATION BY CONSIDERING THE EFFECTS OF MATERIAL PROCESSING AND SERVICE REQUIREMENTS

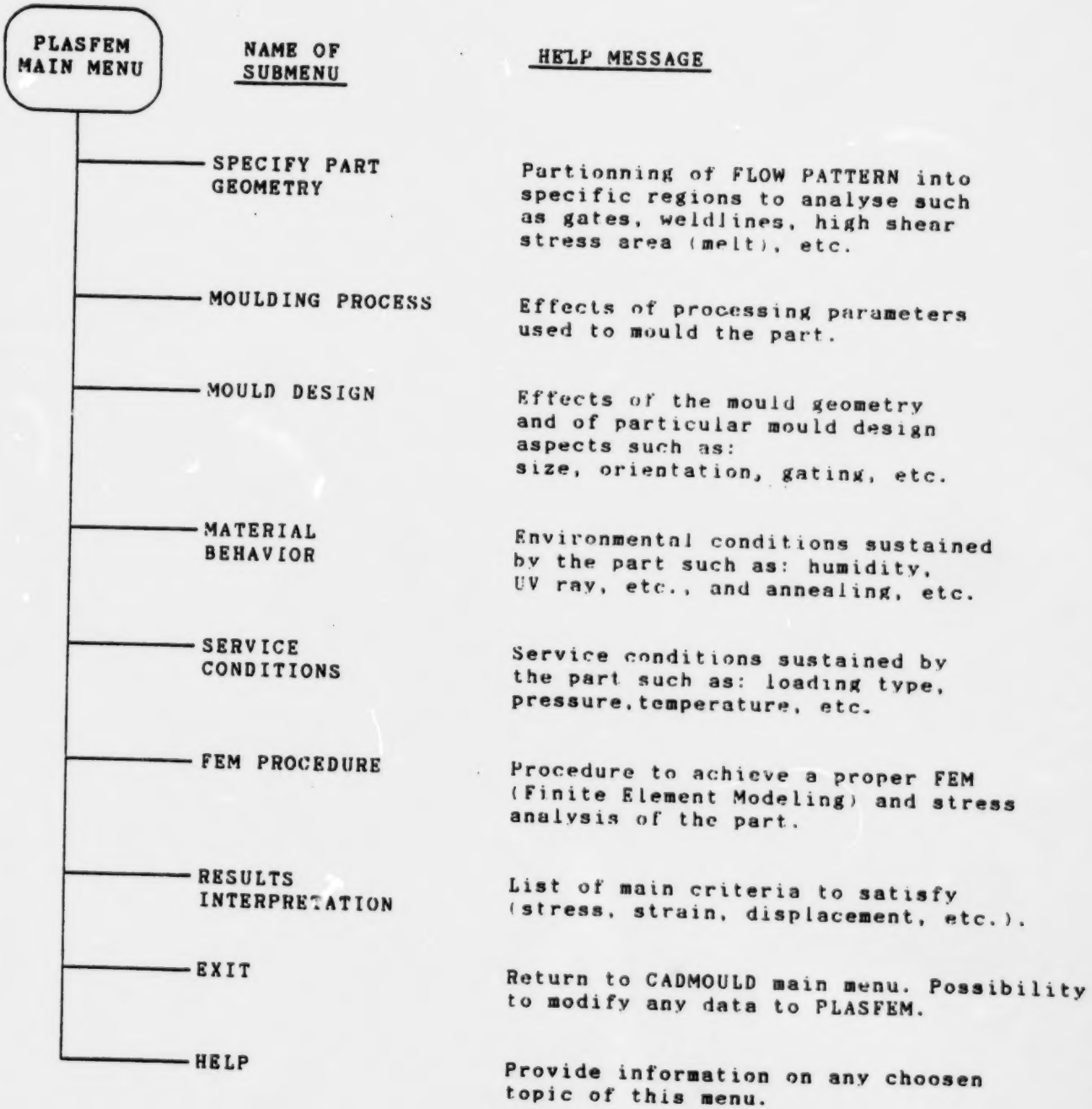

PLASFEM MAIN MENU
NAME OF SUBMENU
HELP MESSAGE
SPECIFY PART GEOMETRY
Partionning of FLOW PATTERN into specific regions to analyse such as gates, weldlines, high shear stress area (melt), etc.
MOULDING PROCESS
Effects of processing parameters used to mould the part.
MOULD DESIGN
Effects of the mould geometry and of particular mould design aspects such as: size, orientation, gating, etc.
MATERIAL BEHAVIOR
Environmental conditions sustained by the part such as: humidity, UV ray, etc., and annealing, etc.
SERVICE CONDITIONS
Service conditions sustained by the part such as: loading type, pressure, temperature, etc.
FEM PROCEDURE
Procedure to achieve a proper FEM (Finite Element Modeling) and stress analysis of the part.
RESULTS INTERPRETATION
List of main criteria to satisfy (stress, strain, displacement, etc.).
EXIT
Return to CADMOULD main menu. Possibility to modify any data to PLASFEM.
HELP
Provide information on any choosen topic of this menu.

Fig. 2 . EXPERT-SYSTEM FOR THE DESIGN ANALYSIS OF MOULDED PRODUCTS

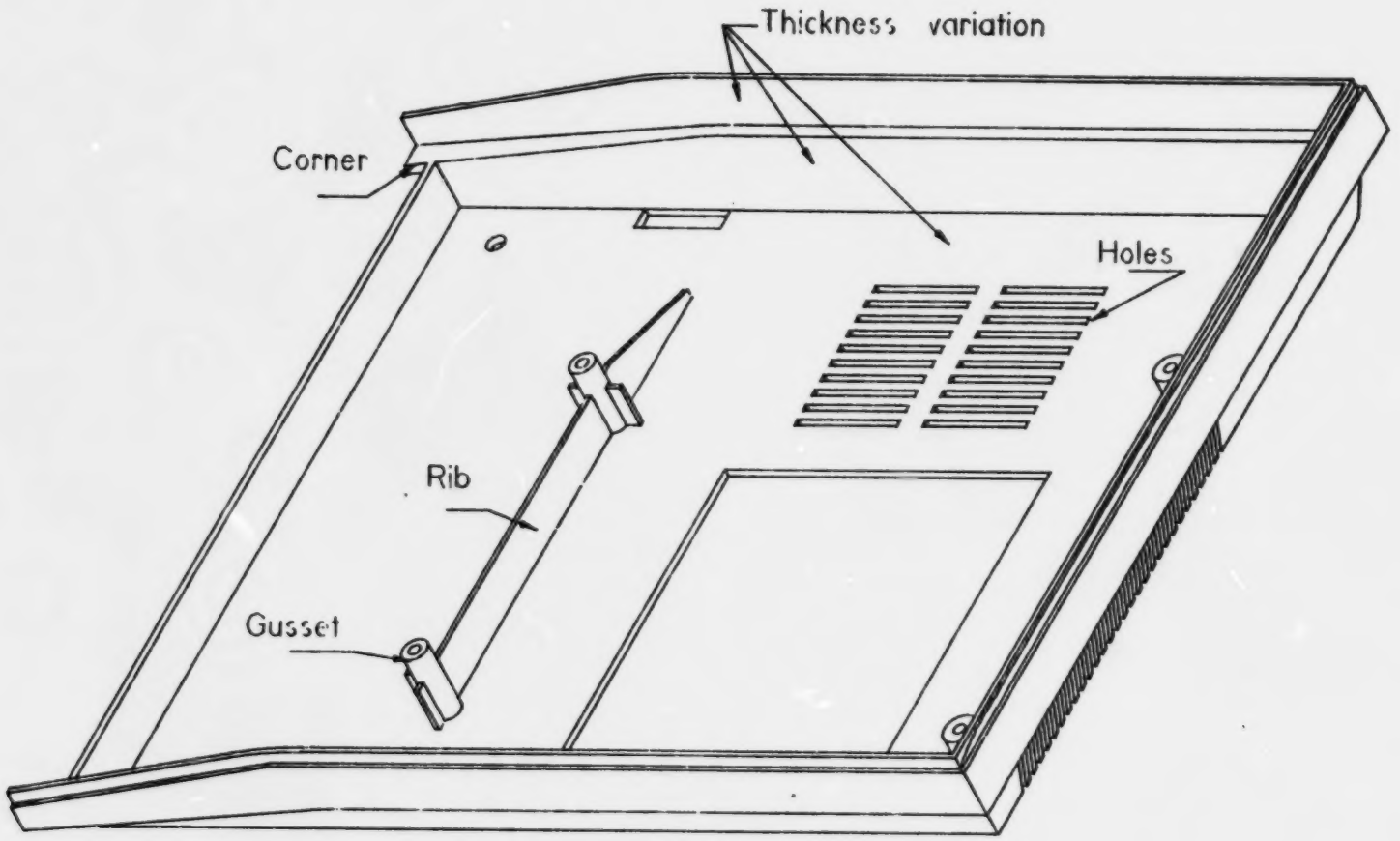
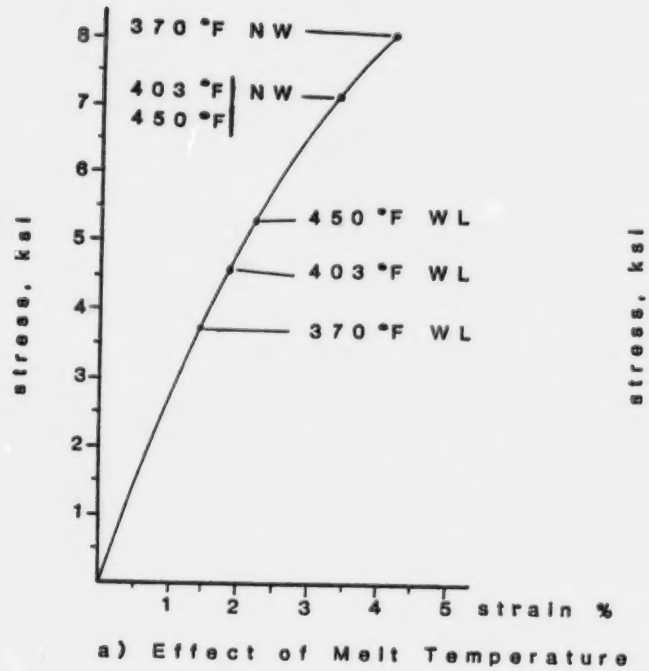
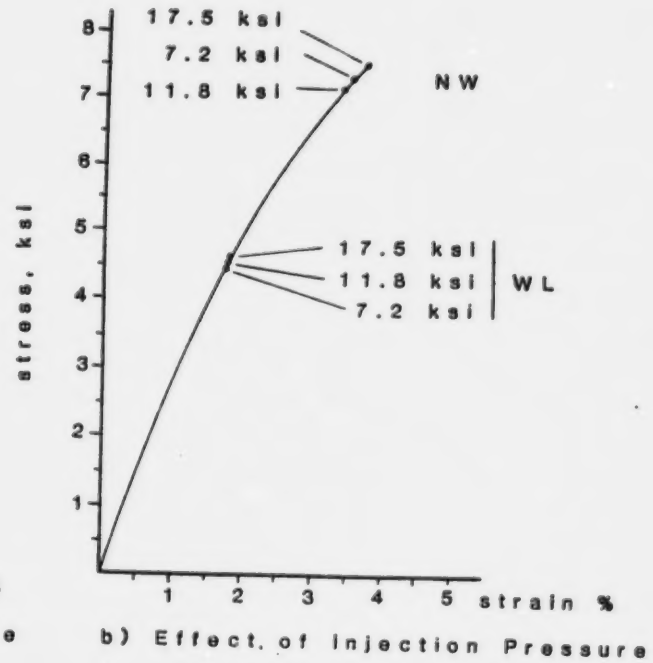


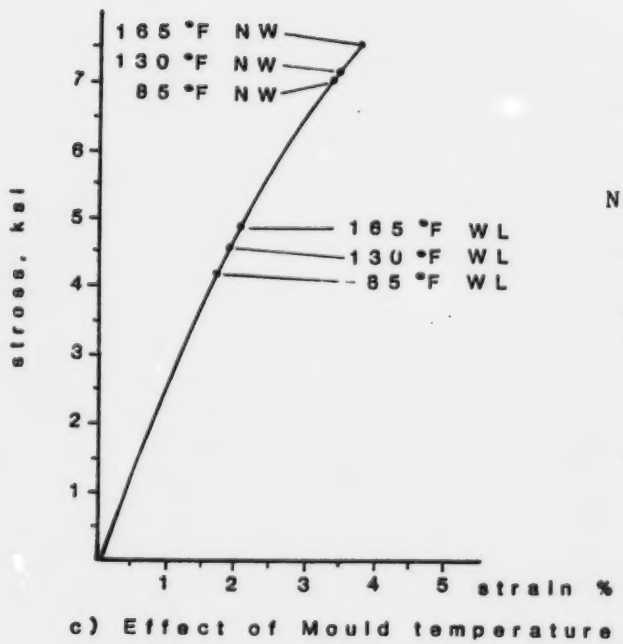
Fig. 3. 3D Solid Model of the Display Phone Bottom Keyboard



a) Effect of Melt Temperature



b) Effect of Injection Pressure



c) Effect of Mould temperature

N.B.: Otherwise indicated,

-Injection pressure: 11.8 ksi
-Melt temperature: 403 F
-Mould temperature: 130 F
-Injection speed: 60 in/min
-Strain rate: 0.2 in/min

-WL ....specimens with weldline
-NW ....specimens without weldline
- • ....break point of the specimens

Fig.4. Effect of Injection Parameters on PS specimens with and without Weldlines

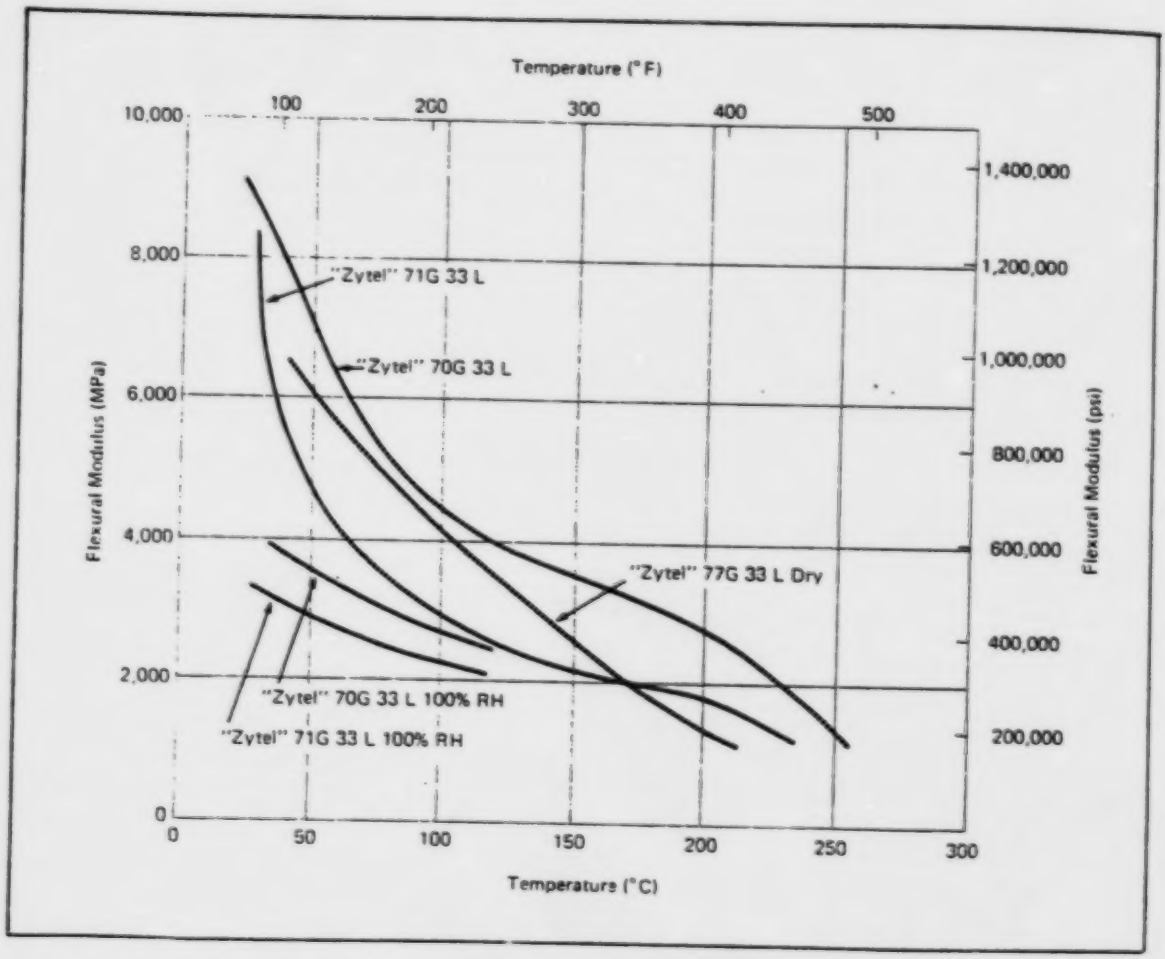


Fig. 5. FLEXURAL MODULUS VS. TEMPERATURE AT DIFFERENT HUMIDITIES. "ZYTEL" 77G 33 L, 70G 33 L, 71G 33 L

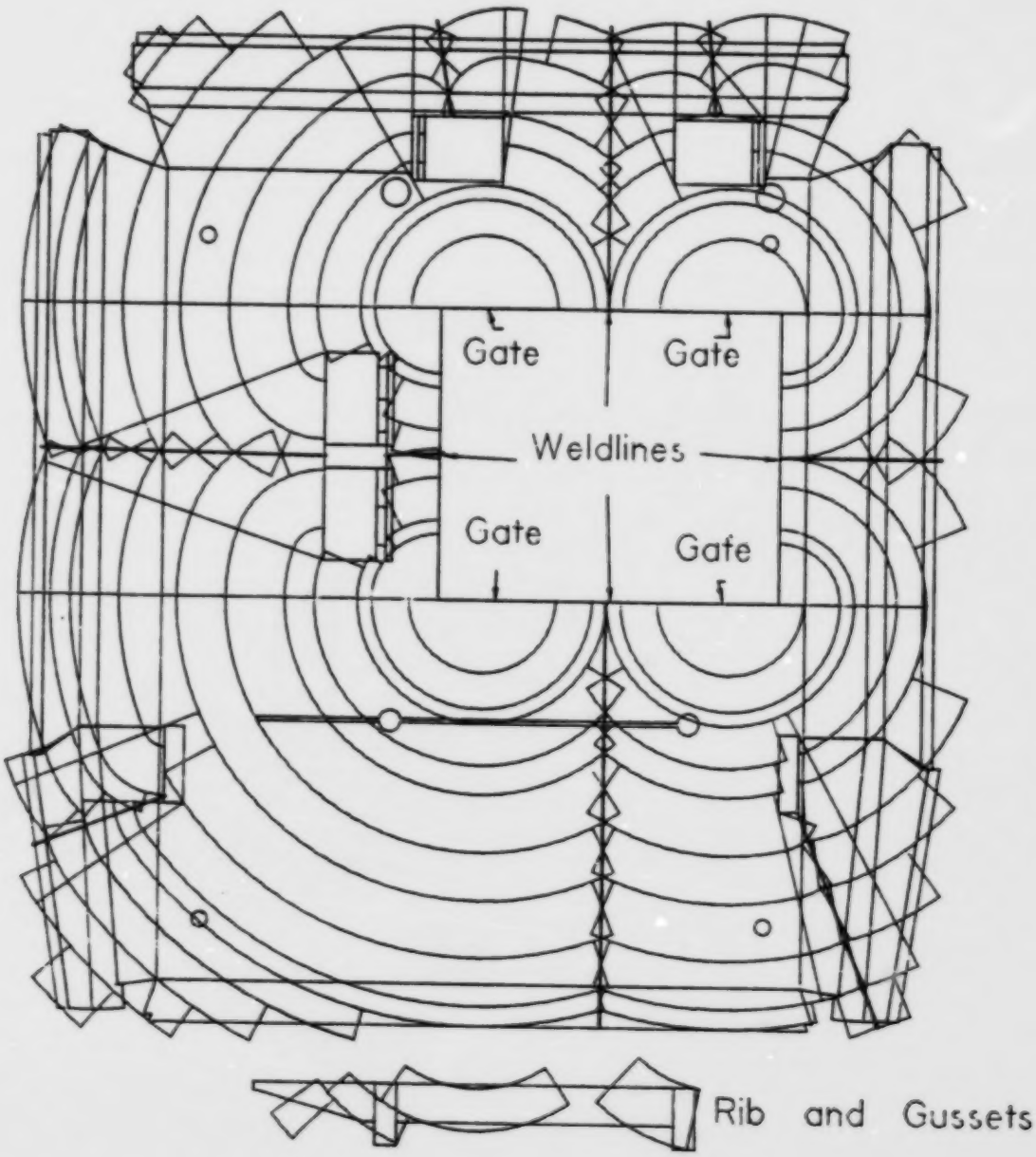
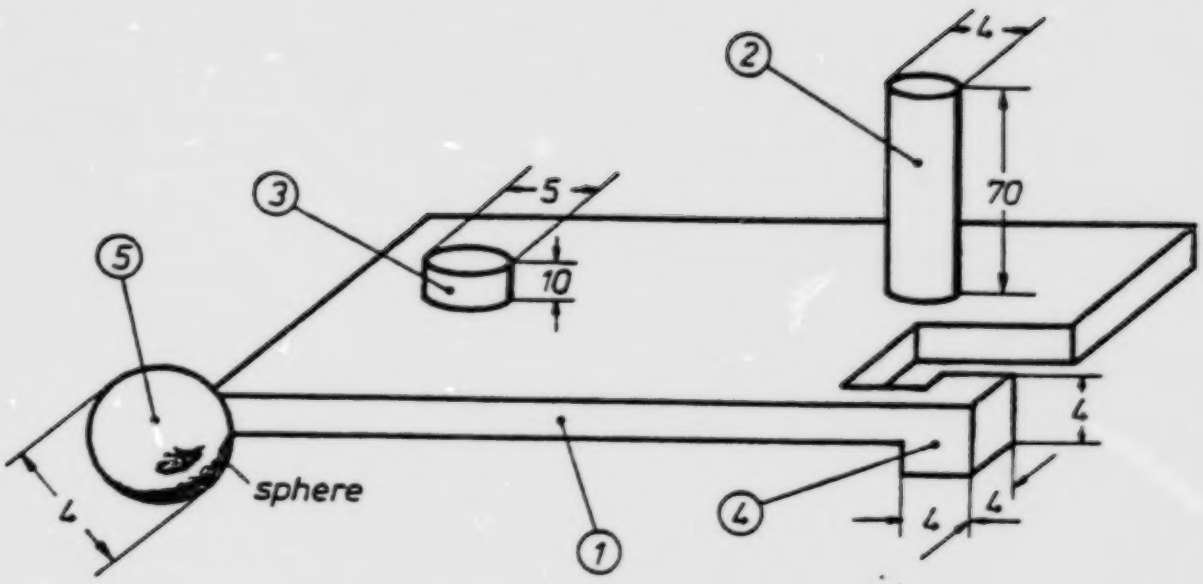


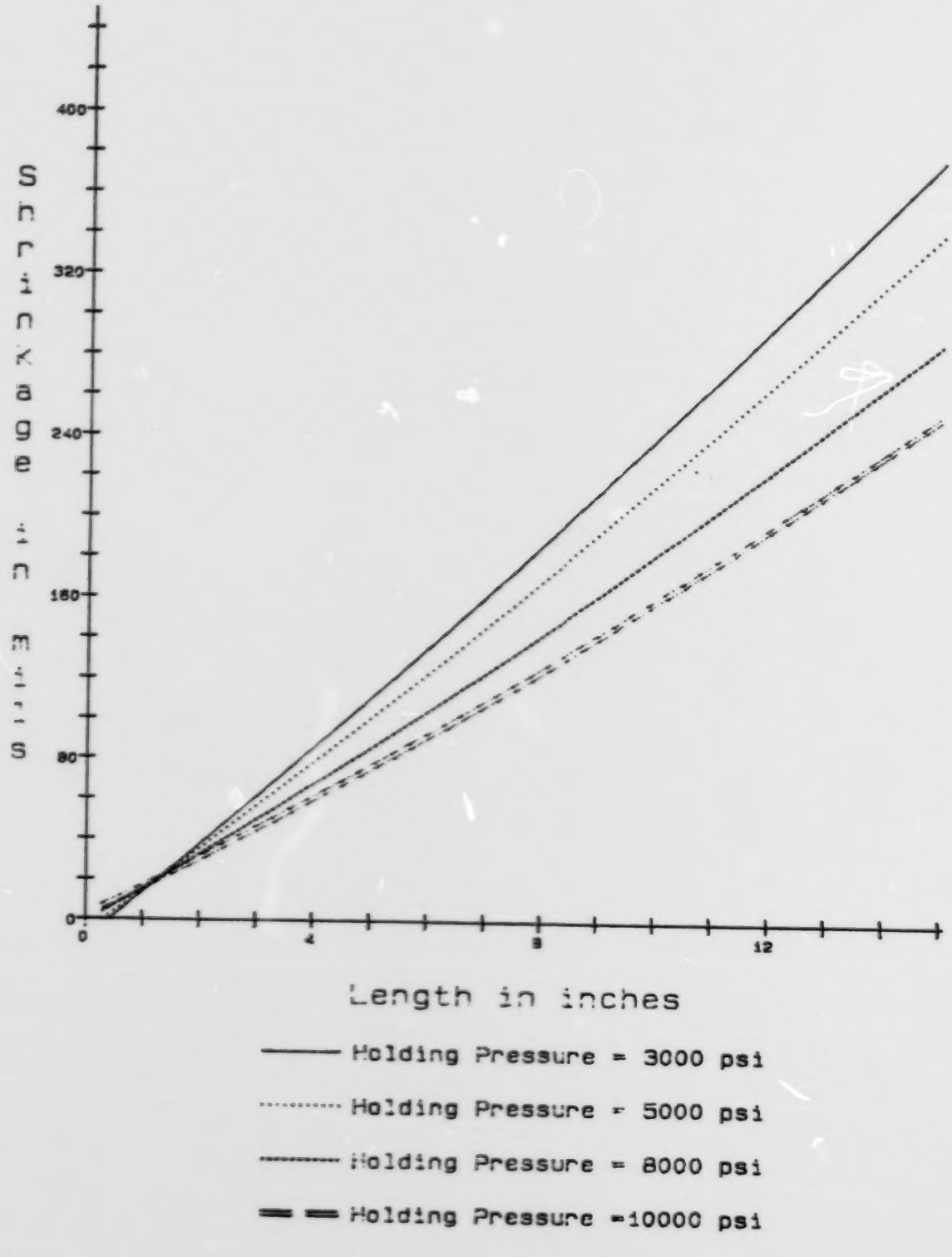
Fig 6 Flow Pattern During the Filling Phase of the Keyboard



- 1: Plate
- 2: Long Cylinder
- 3: Short Cylinder
- 4: Cube
- 5: Sphere

Fig. 7: Primitive geometries for the cooling time analysis

Fig. 8. Variation of Longitudinal shrinkage Along Flow Path for a .187 Thick Plate and a Cooling Time of 38s.



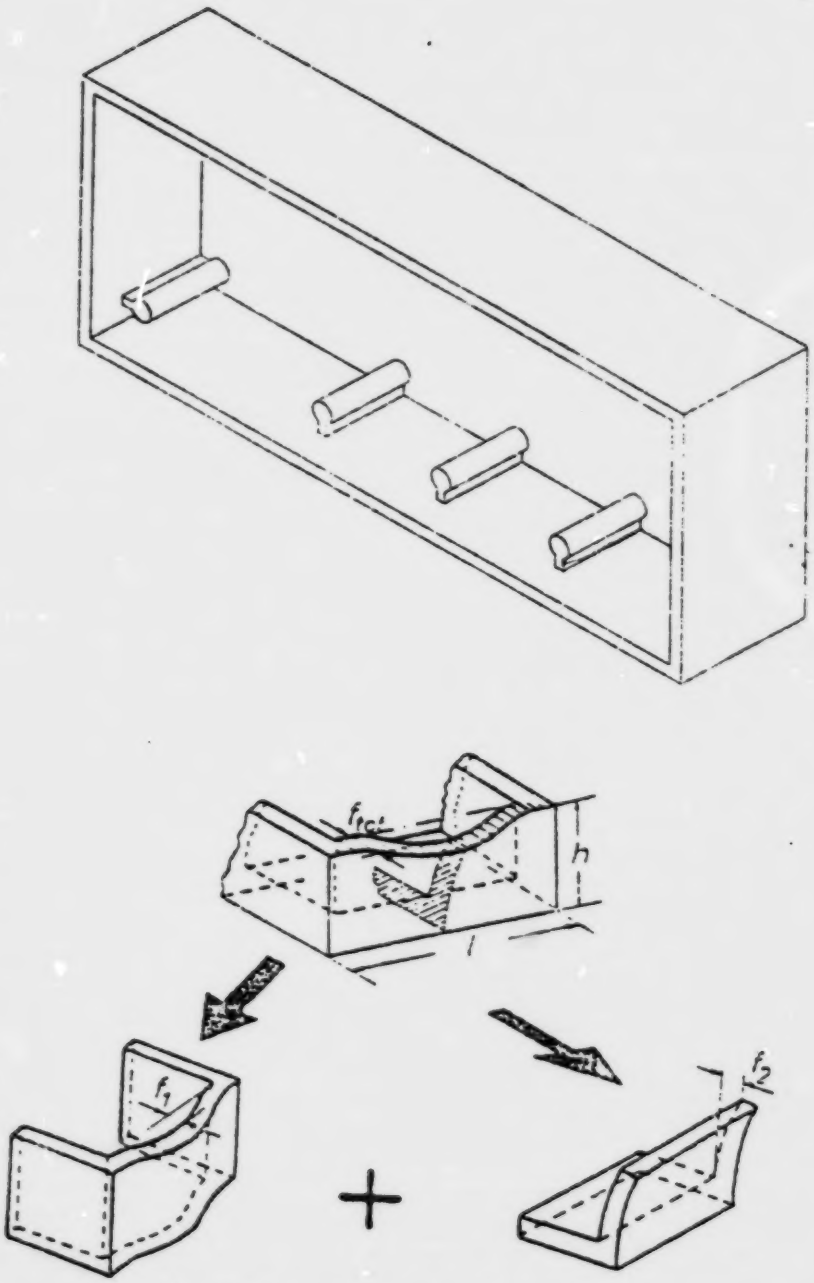
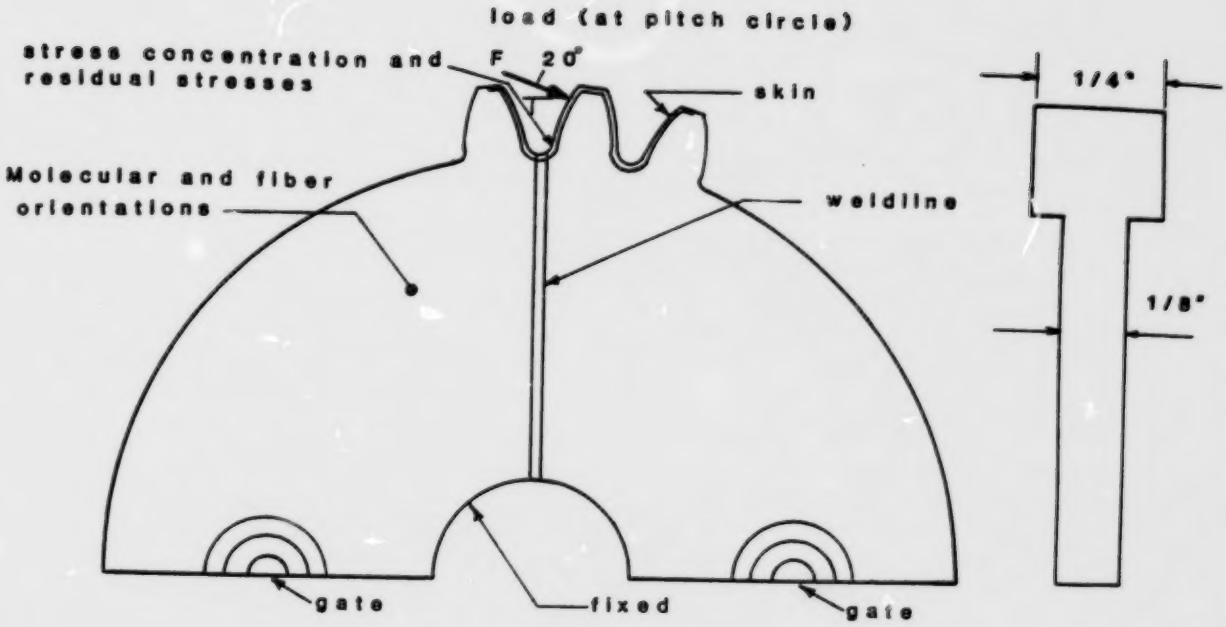
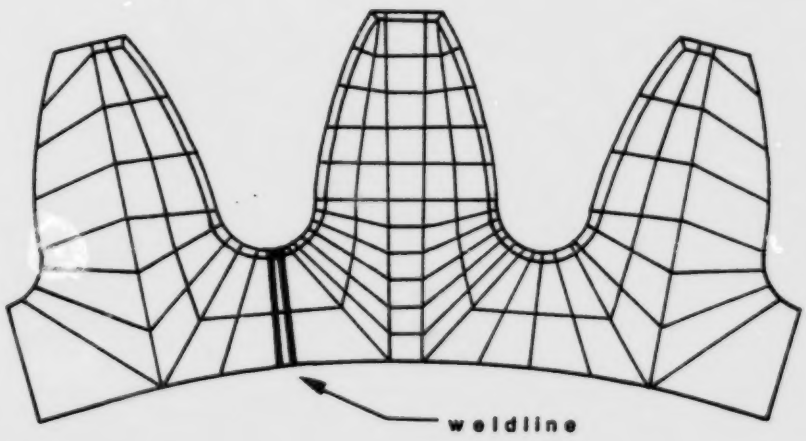


Fig. 9: Design Optimization of a Box Shaped Experimental Mould



a) Boundary conditions - Loading and Particular regions



b) Finite element meshing - tooth part

Fig. 18: Modelling of an injected moulded gear for finite element analysis

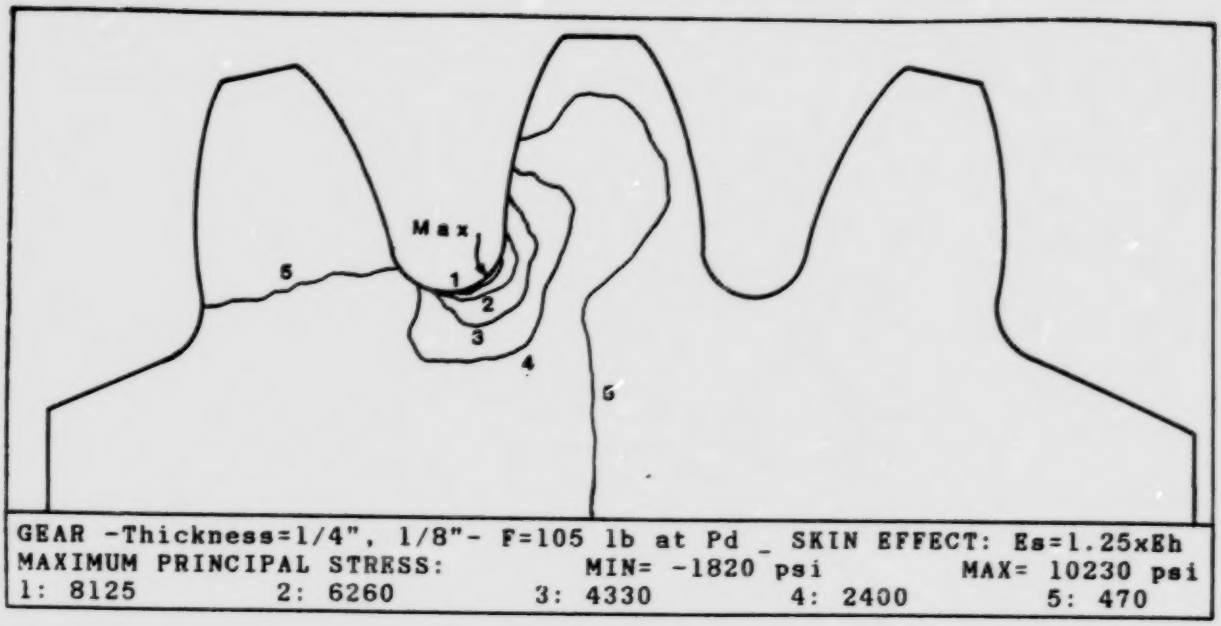


Fig. 11: Maximum principal stress distribution - Case of skin effect (elastic modulus in the skin = 1.25 x modulus in other area)

Table 1: Effect of the elastic modulus of a specific region on the mechanical behaviour of the part

Case	Assumed Elastic Modulus (ksi)	Maximum Stress		Displacement		Allowable Stress Limit(ksi)	Note
		Value (ksi)	Variation (%)	Value (in)	Variation (%)		
Homogeneous Material	Eh=320	8.94	----	0.0194	----	9.0	1
Skin E+ Es=1.25xEh	Eh=320 Es=400	10.23	14.4	0.0190	2.1	9.0	2
Skin E- Es=0.75xEh	Eh=320 Es=240	7.38	17.5	0.0201	3.6	9.0	1
Weldline 1 Ew=0.50xEh	Eh=320 Ew=160	8.82	1.3	0.0198	2.1	4.5	2
Weldline 2 Ew=0.75xEh	Eh=320	8.90	0.5	0.0196	1.0	4.5	2

Note: 1) Part design is satisfactory under these conditions.

2) Part design is unacceptable under these conditions since the allowable stress limit is exceeded.

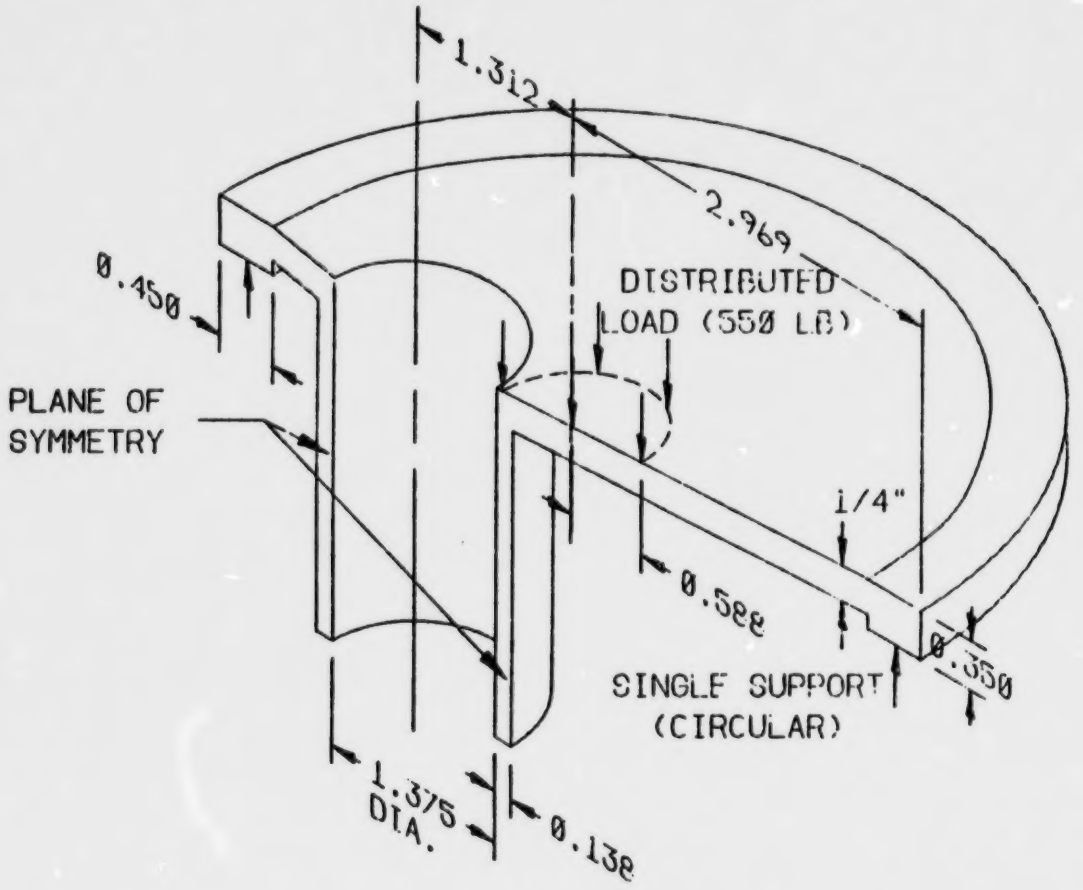


Fig. 12. Floor Drain - Half Part of Original Model

- Loading and Boundary Conditions

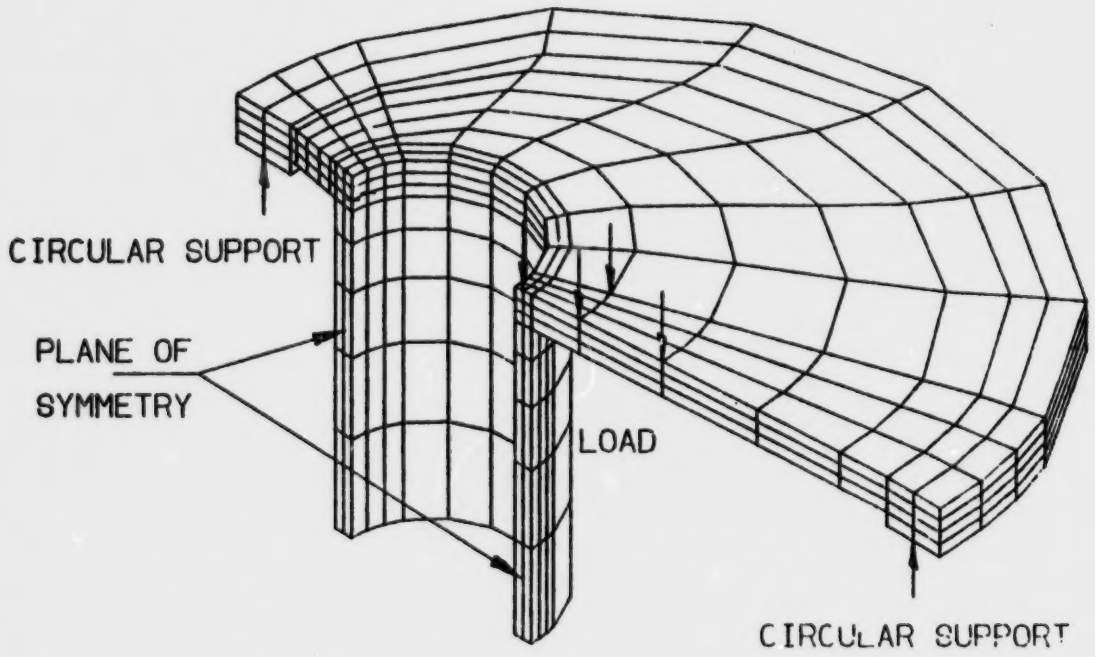


Fig. 13. Modelling of a Floor Drain for Finite Element Analysis

MAXIMUM PRINCIPAL STRESS DISTRIBUTION: MIN=-3658 MAX=31910 PSI

1: 2346 2: 8259 3: 14170 4: 20090 5: 26000 PSI

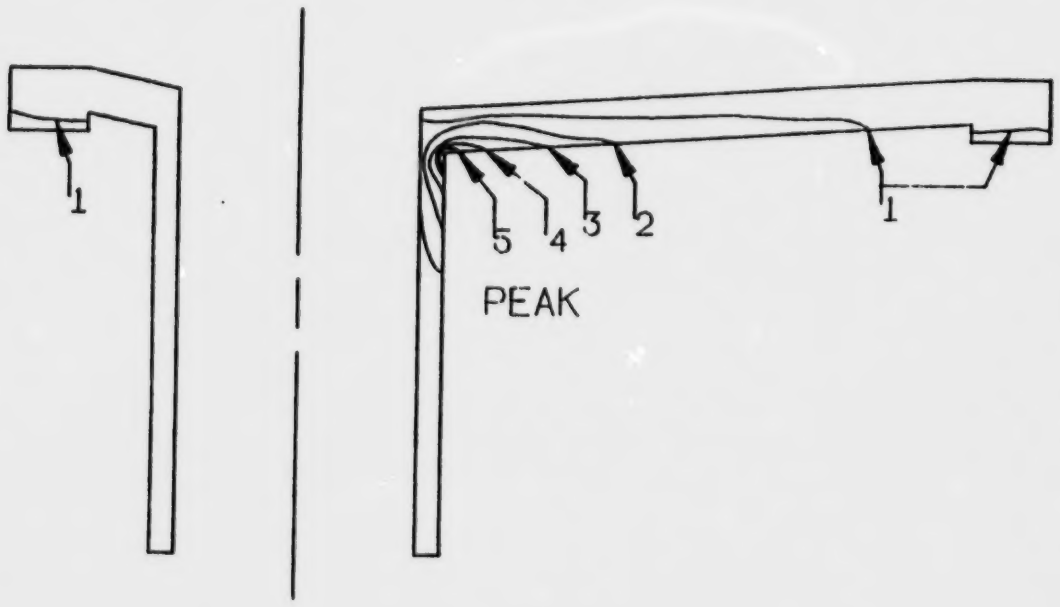


Fig. 14. Stress Distribution Through the Plane of Symmetry

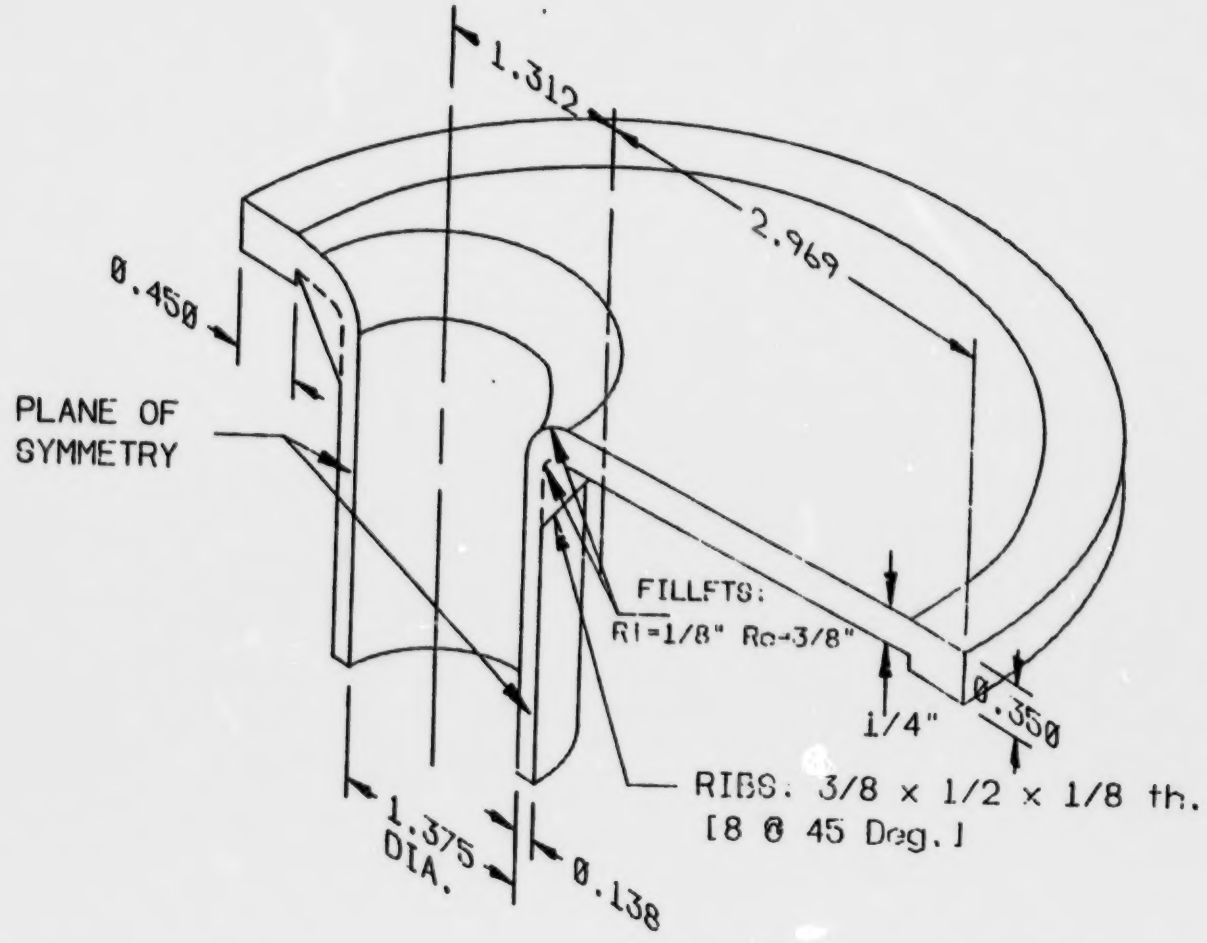


Fig. 15. Optimized Floor Drain Geometry - (Half Part)

MAXIMUM PRINCIPAL STRESS DISTRIBUTION: MIN=-3646 MAX=14600 PSI

1: -417 2: 2563 3: 5544 4: 8525 5: 11510 PSI

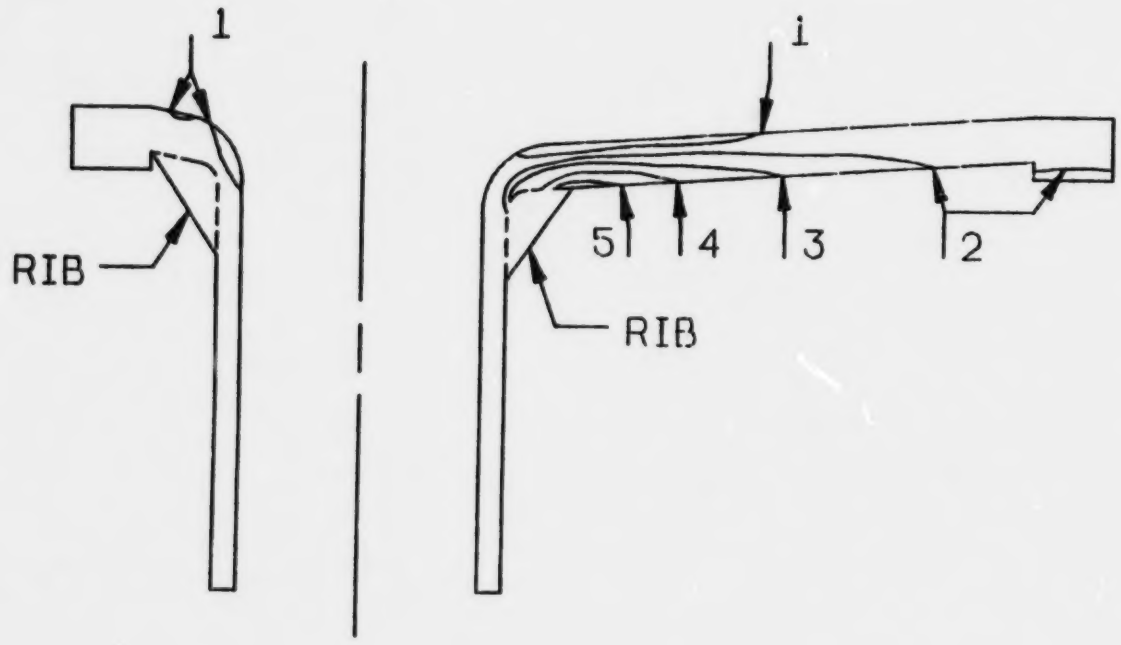


Fig. 16. Final Stress Distribution Through the Plane of Symmetry

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CNRC 26209

LA SIMULATION PENDANT LA CONCEPTION DE MOULES D'INJECTION
DESIGN ANALYSIS AND SIMULATION OF INJECTION MOULDS

par/by

Georges SALLOUM, Patrick GIRARD, Denis CHARLAND
C.N.R.C., Institut de génie des matériaux

English

This presentation describes the advantages of using an interactive software package based on solid modelling for the design and simulation of injection moulding.

An expert system can assist the user in the decision making process at any time during the development of the mould. Starting with the solid representation of the part, the mould is constructed with the help of interactive graphic menues, supported by a flexible database.

A parametric database has been developed by taking into account the design and manufacturing guidelines, material characteristics and information on tooling and polymer processing. A flow simulation program allows the user to analyze the filling of the mould and optimize the operating conditions. The design of the feeding systems will follow and a complete analysis can be performed during the design of the cooling and the mechanical systems.

Français

Cette présentation décrit les avantages de l'utilisation d'un logiciel interactif de conception et d'analyse des moules uilisant une représentation volumique de la pièce. Un sytème expert aide l'utilisateur lors du processus décisionnel à n'importe quel moment durant la période de développement du moule.

A partir de la représentation volumique de la pièce, le moule est construit avec l'aide de menus interactifs, soutenus par une base de données flexible. Une base de données paramétrique a été mise au point qui tient compte des recommandations de conception et de fabrication pour l'outillage et la mise en oeuvre des polymères.

Un logiciel de simulation de l'écoulement permet à l'utilisateur d'analyser la phase de remplissage du moule et d'optimiser les conditions d'opération. Le design des canaux d'injection vient ensuite, ainsi qu'une analyse du système de refroidissement et de la mécanique du moule.

INTRODUCTION

The design of injection moulds involves flow, thermal, mechanical and cost analyses. Starting with a solid representation of the part, the mould is constructed with the help of databases which provide information on tooling, materials and processes. An expert system can assist the designer in the decision making process at any time during the development of the mould.

Over the past few years, work has progressed toward the acceptance of solid modelling technology, which represents the key to computer integrated injection moulding. This paper describes the capabilities of an integrated software that goes beyond the geometric construction of the mould and provides the bridge to link the design step to other engineering simulations and improves the manufacturing process of injection moulds. Key factors such as end user requirements, modularity and reliable information are at the core of this development. Today, mould designers are under pressure to make the right decision soon enough so as not to hold up other design or planning operations.

1. COMPUTER INTEGRATED INJECTION MOULDING

A computer integrated injection moulding system (CIIM) requires a combination of computer hardware and software for product design, planning and manufacturing. It can be seen as a synthesis of the following technologies:

- Database management.
- Computer graphics.
- Mathematical modelling.
- Production control.

Applications such as material evaluation, product design, mould design and process planning can be supported. The aim of computer integrated injection moulding is to understand the material behavior during the total moulding cycle. This means the ability to simulate a given process, for an optimum design of products and tools. The information gathered during the simulation can be transferred later onto the moulding machinery. The results can also be used to optimize production cycle, tool life, material flow and energy conservation.

With an integrated system the database created during the design phase might become a bill of material, or it can provide processing parameters to machine the mould or to produce the part. A process simulation might answer questions about producibility or end product quality. Naturally, the engineering simulations are limited to problems that are understood well enough to be described with a mathematical modelling approach.

This software was designed with the end user requirements in mind, it features:

- Inherent design methodology and flexibility
- Direct access to material dependent design parameters
- A standard set of geometric primitives for runners and gates
- Internal diagnostics to help quickly isolate potential design problems.

The design process begins with a solid representation of the part to be moulded as illustrated in figure 1. A material database provides the designer with the properties of the resins, mould materials and cooling liquids. These properties can be constants or variables. A mechanical analysis can then be performed to determine the optimum shape and thickness of the part. The mould type, number of cavities and capacity of the moulding press are then chosen by taking into consideration the part specifications and other requirements. At this stage, the layout of the mould at the parting line can be done.

2. APPLICATION TO THE DESIGN OF MOULDS

Presently, the design steps of the feeding system involve sketching alternative concepts or paging through reference books and moulding manuals or personal notes. PLASFEED, a newly developed software can help the mould designer to meet his application requirements with a library of special functions.

The software has a variety of extended features which add functionality and performance needed for the production of injection moulds. The software consists of a parametric database with an advanced menu driven interface that supports the construction of a wide variety of runner and gate configurations. Also, this knowledge-based software consists of a set of graphics support procedures for faster and more efficient design process. It captures the most common design practices and guidelines for different moulding materials.

The first module consists of eight primitives in a natural format for the design of runners. The menu shown in figure 2 is intended for an automatic selection and display of these primitives . Primitives can be connected at any time to construct the complete runner system. This module can support round and trapezoidal runner cross sections. Another possibility is to diagnose existing design alternatives for evaluation and correction. Once the preferred design is selected, the geometric construction involves specifying the exact dimensions of these primitives. A typical example is shown in figure 3 for an S shape.

The second module lets the designer rapidly create the gating system. Once the appropriate gate is selected from the main menu infigure 4, the designer should input the design parameters. This can be done through an on line access to reference documentation as illustrated in table 1. The user can interactively select the resin to be moulded and input these design parameters which are material dependent. Design modifications are possible since the system can automatically update the model. Typical examples are shown in figures 5 and 6 for submarine and pinpoint gates respectively.

The software has been sucessfully applied to many feeding systems configurations. The distributed architecture permits the designer to select, combine and modify the design primitives. As such, the solid modeler provides commands to copy, scale or mirror the model. As illustrated, in figure 7, the primitives can be merged together to construct the complete feeding system. Then, the same geometry can be segmented for the melt flow analysis or flow balancing in a family mould. Also the solid model of the feeding system can be substracted from the cavity plate to obtain the negative, as shown in figure 8.

Therefore, many design alternatives can be evaluated to ensure that the selected feeding system will meet all operational objectives including shape, size, weight and cost. In addition, the solid modeler allows the designer to examine the feeding system from different angles. The model may be viewed in section with hidden line removed or as shaded image on a raster screen.

3. MOULD FILLING SIMULATION

The flat pattern for the flow analysis is then prepared from the wire frame representation of the part. As shown in figure 9 an equivalent representation of the filling pattern is developed based on the flow of the resin in the mould. Several mathematical equations governing the material behavior are available.

The results are then displayed with an appropriate sotware interface on the graphics workstation as curves or shaded plot contours. This is illustrated in Figure 10. Also, the program will flag the user if the calculated values are outside the practical range for the material.

The flow analysis provides the following information:

- Pressure drop in the mould.
- Temperature variation along the flow paths.
- Shear rates and shear stresses.

Also, the program helps balancing feeding channels, multiple gating systems and family moulds. The approximate model already generated during the construction of the feeding system can be processed for the calculations of mass properties and the boundary file (exact 3D mathematical representation of the solid model). Furthermore, this information may be used as a basis for the calculation of regrind, shot size and cost estimation or CNC tool path generation.

Processing limitations for a given resin such as maximum and minimum part thickness, melt temperature and injection pressure are implemented in the same database. Recommended clamping tonnage, screw speed, filling time, etc. are also available. The designer can choose practical values to start the analysis or to check if the results are within these limitations. The designer should also be able to modify the geometry to reflect any changes that might occur as a result of these calculations.

4. MOULD COOLING SIMULATION

An optimum design of the cooling channels can be performed based on a minimum cooling cycle and a given mould surface temperature variation. As shown in Figure 11, the thermal balance (mould, part, environment) helps predict the cooling liquid flow rate and supports the following applications:

- Positioning and dimensioning of the cooling channels.
- Optimization of the operating conditions such as flow rate, temperature and pressure.
- Taking into account the influence of mould insulation and hot runners.

5. MOULD SHRINKAGE SIMULATION

The prediction of shrinkage has always been a major problem for mould designers and moulders. The usual practice is to estimate shrinkage from data as published by the raw materials suppliers or from past moulding experience. Since moulding shrinkage is not uniform in all directions this often leads to many modifications of the cavity and core and occasionally to a complete retooling. Therefore, a computer assisted calculation of linear shrinkage that can be used in conjunction with the previous melt flow and mould cooling simulations is of great value to mould designers during the dimensioning of injection moulds. Moulding shrinkage can be predicted by models incorporating moulding parameters (holding pressure, injection pressure, mould temperature, material temperature, cooling time); intrinsic material properties (melt viscosity, heat capacity, density, conductivity), and part geometry (locations, dimensions and thickness).

6. MOULD MECHANICAL SIMULATION

The mechanical behavior of the mould under the hydraulic pressure and the clamping force can be predicted during the moulding cycle. A menu of typical applications is presented in figure 12. The program assists in the following calculations:

-Deflection of a single element with a preset load.

-Minimum wall thickness of a single element for a preset deflection

-Total deflection determined by superposing the deflections of the mould, press platens and tie bars.

Since the programs are interactive, a constant feedback is given at any step and the design process ends when the operating conditions have been optimized.

CONCLUSIONS

We have seen the advantages of using an expert system in the design process of injection moulds articulated around the solid modelling technology. This article presents a way to effectively chain some interrelated technologies such as injection moulding, polymers engineering and tool design and manufacturing. The experience, knowledge and judgement of moulders, mouldmakers and product designers are implemented in such a system.

Through a generic problem solving architecture, this will enable the user to realize substantial improvements during the product development process. Qualified mould designers can expand their capabilities to provide excellent solutions, put more control where it is required and produce higher quality products and moulds.

EDGE GATE

MATERIAL	T	H	W	L	N
ABS	<= 2.4mm	1.6 - 2.4mm	2.4 - 3.2mm	<= 1.0mm	0.7
	2.4 - 3.2mm	2.4 - 3.2mm	3.2 - 6.4mm	<= 1.0mm	0.7
	3.2 - 4.0mm	3.2 - 4.0mm	6.4 -13.0mm	<= 1.0mm	0.7
ACETAL	<= 3.0mm	<= 1.5mm	<= 1.0mm	<= 1.0mm	0.7
NYLON	<= 0.8mm	<= 0.8mm	<= 1.1mm	0.8 - 1.3mm	0.5
	0.8 - 3.0mm	1.3 - 2.0mm	1.3 - 2.0mm	0.8 - 1.3mm	0.5
	3.0 - 6.0mm	1.5 - 3.6mm	1.5 - 3.6mm	0.8 - 1.3mm	0.5
POLYESTER PBT	<= 0.8mm	<= 0.4mm	<= 0.5mm	0.5mm	0.7
	0.8 - 2.5mm	0.4 - 1.0mm	0.8 - 2.5mm	0.5mm	0.7
	2.5 - 3.0mm	1.0 - 1.5mm	2.5 - 3.0mm	0.5 - 0.8mm	0.7
	3.0 - 6.0mm	1.5 - 3.0mm	3.0 - 6.0mm	0.8 - 1.5mm	0.7
PP	<= 6.0mm	0.5 - 3.0mm	0.5 -25.0mm	<= 1.0mm	0.7
PPO	<= 1.5mm	<= 1.5mm	<= 3.0mm	0.5 - 1.0mm	0.9
	1.5 - 6.5mm	1.5 - 3.2mm	3.0 - 6.3mm	0.5 - 1.0mm	0.9

Table 1. Dimensioning table

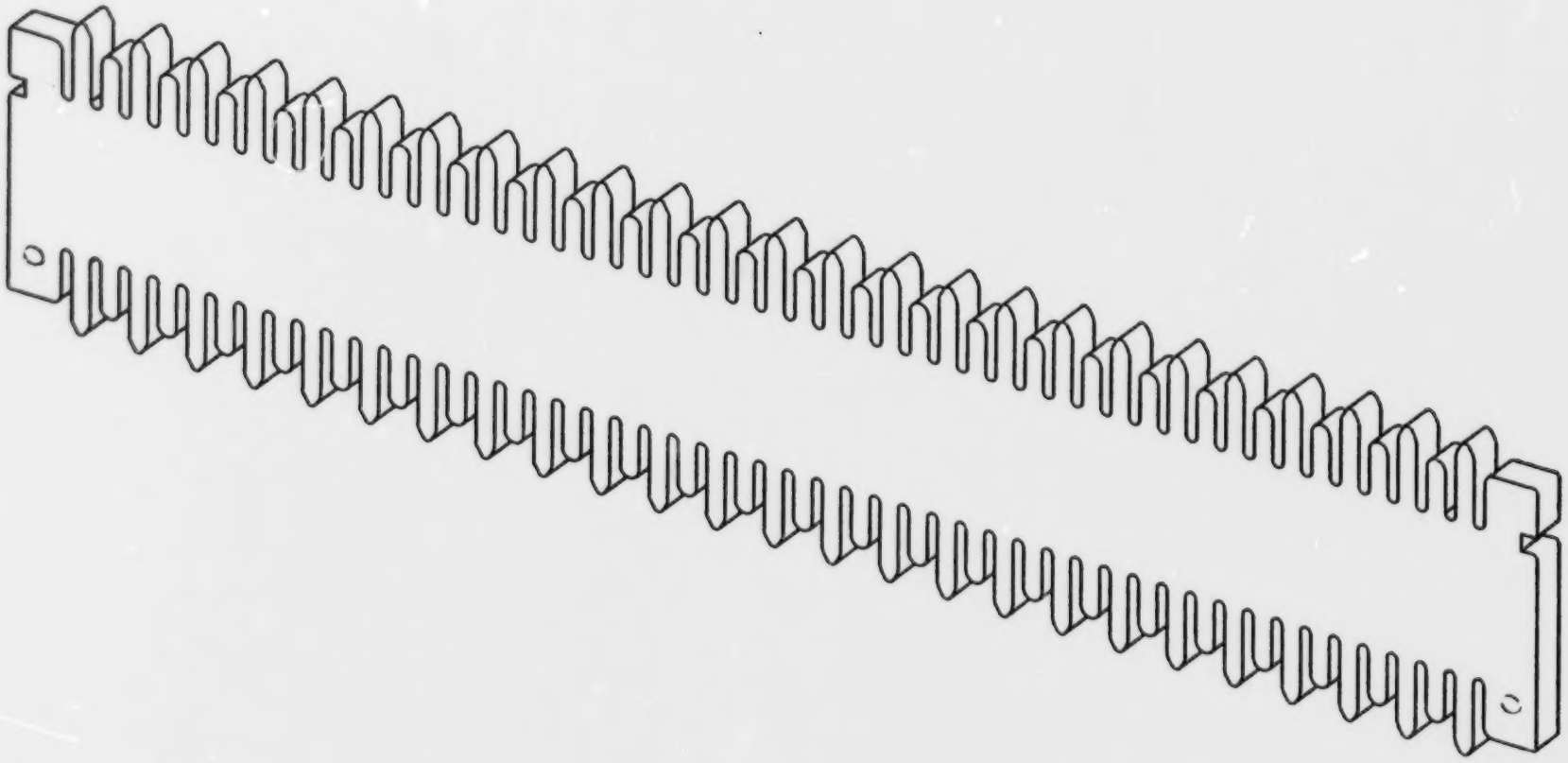


Fig. 1: Solid Representation of the Part

Select runner shape:

F01 STAR
F02 LINEAR
F03 CURVED
F04 L-SHAPE
F05 T-SHAPE
F06 S-SHAPE
F07 U-SHAPE
F08 H-SHAPE

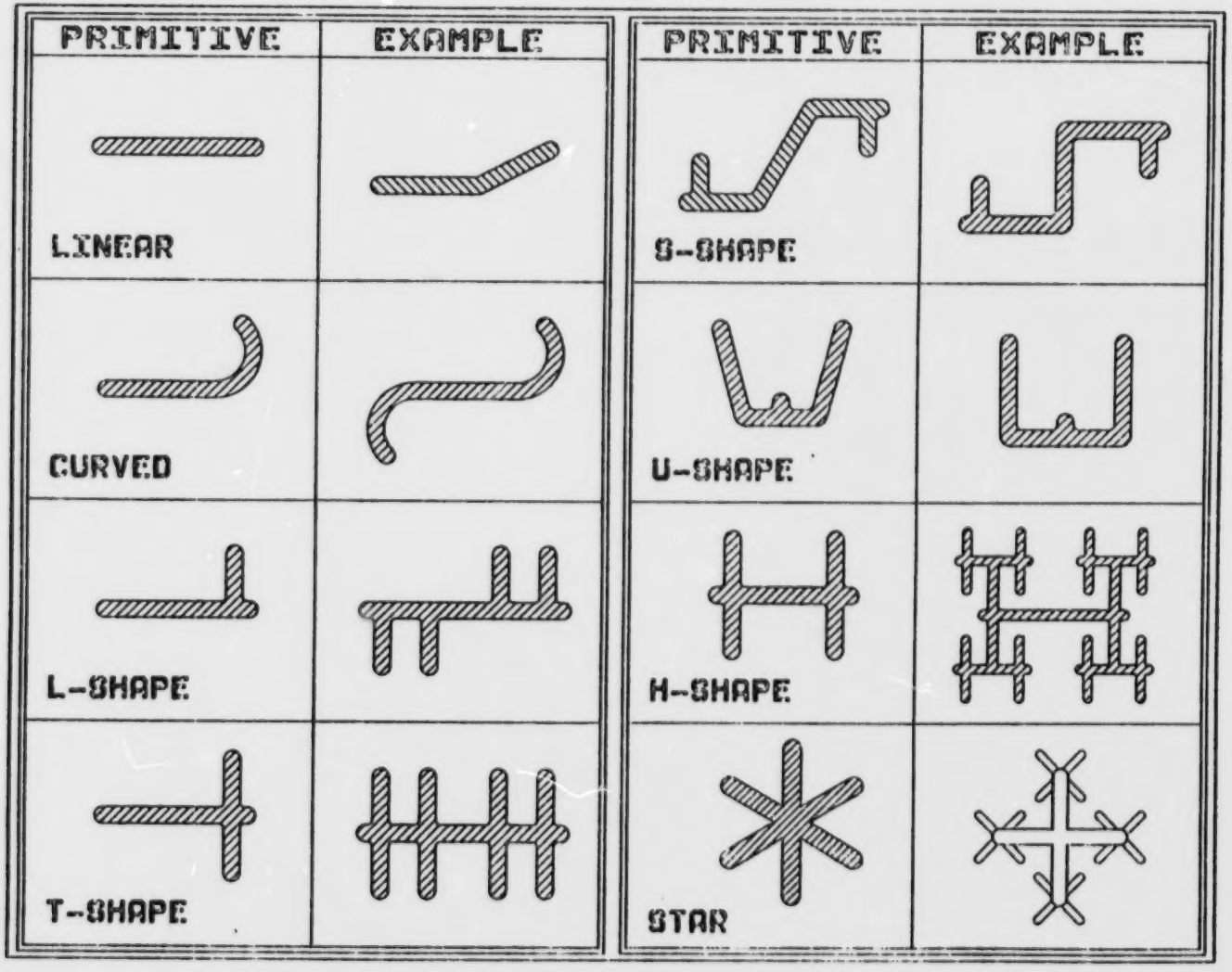


Figure 2, Graphic menu for the design of runners.

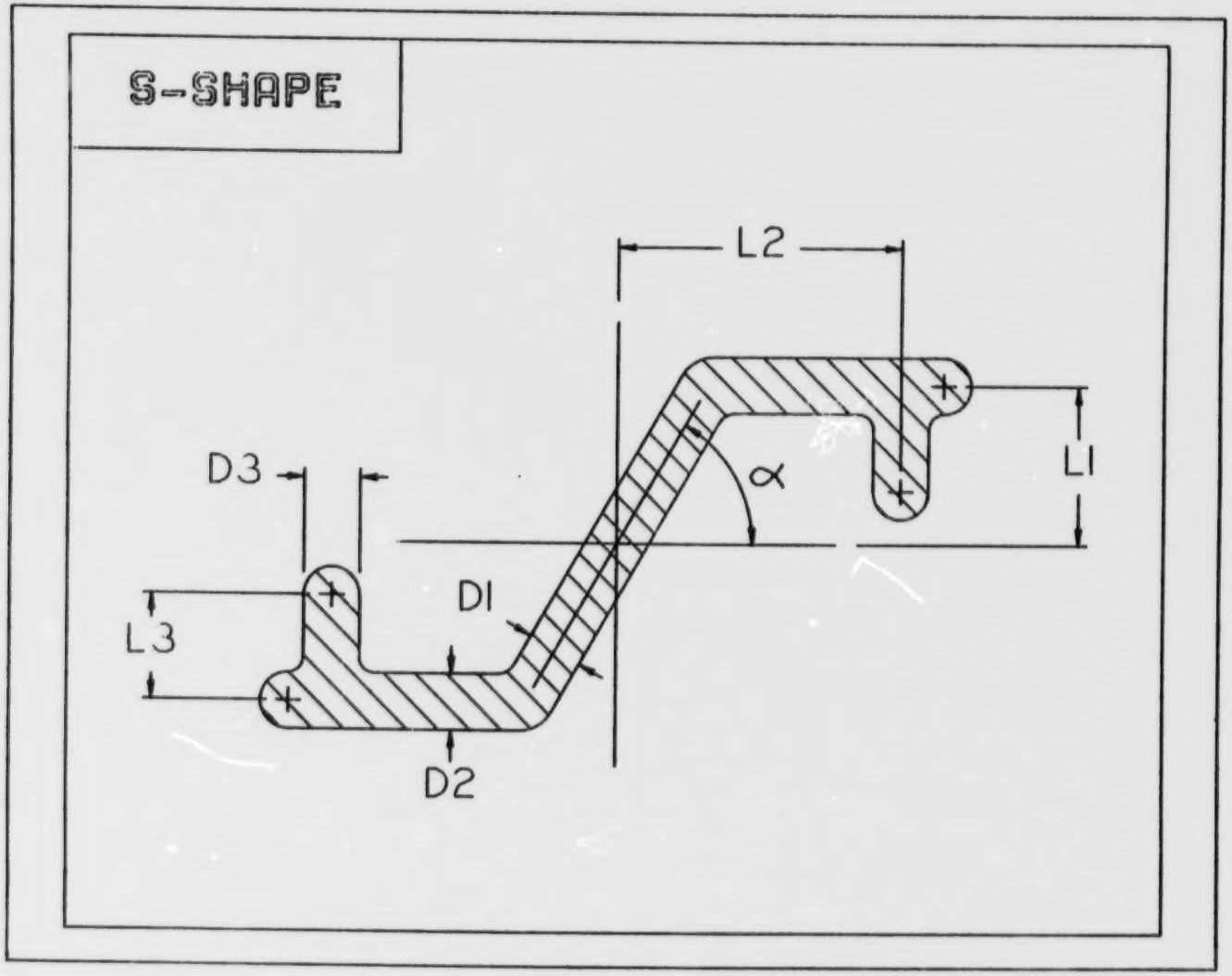


Figure 3, Typical example of an S runner design.

Select gate type:

F01 EDGE
F02 OVERLAP
F03 TAB
F04 FLASH
F05 FAN
F06 DISC
F07 RING
F08 FUNNEL
F09 SUBMARINE
F10 CURVED TUNNEL
F11 PINPOINT

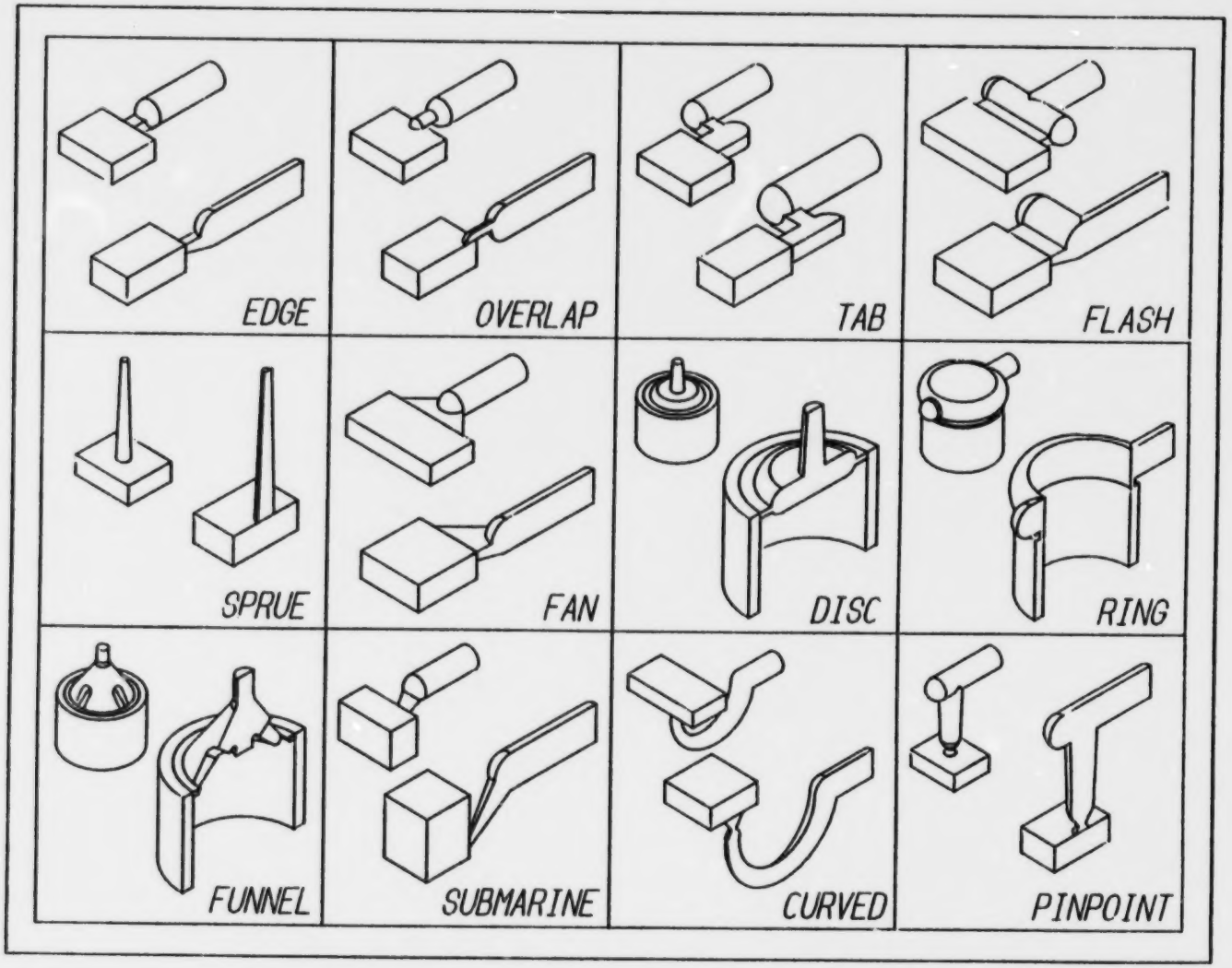


Figure 4, Graphic menu for the design of gates.

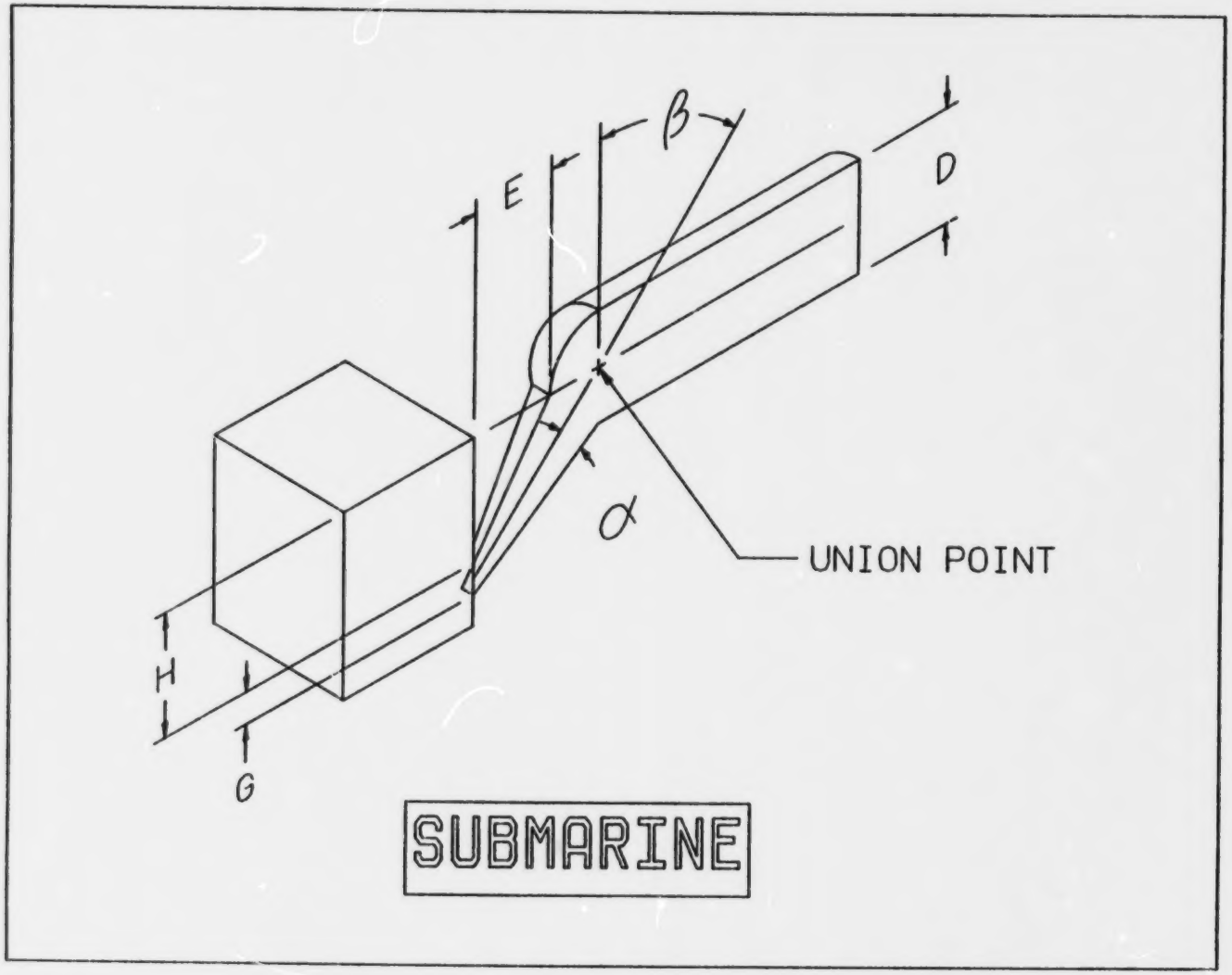


Figure 5, Typical example of a submarine gating system.

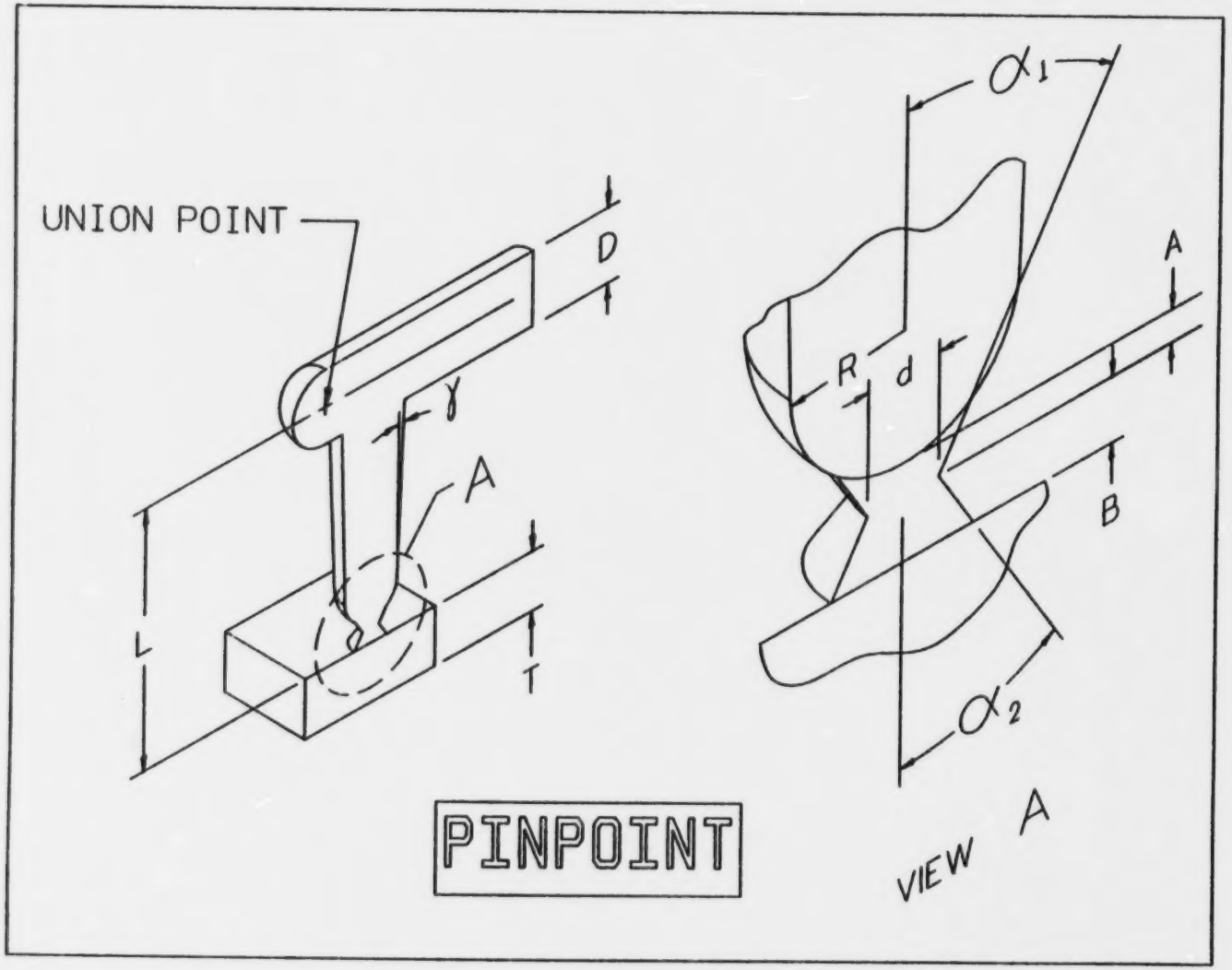


Figure 6, Typical example of a pinpoint gating system.

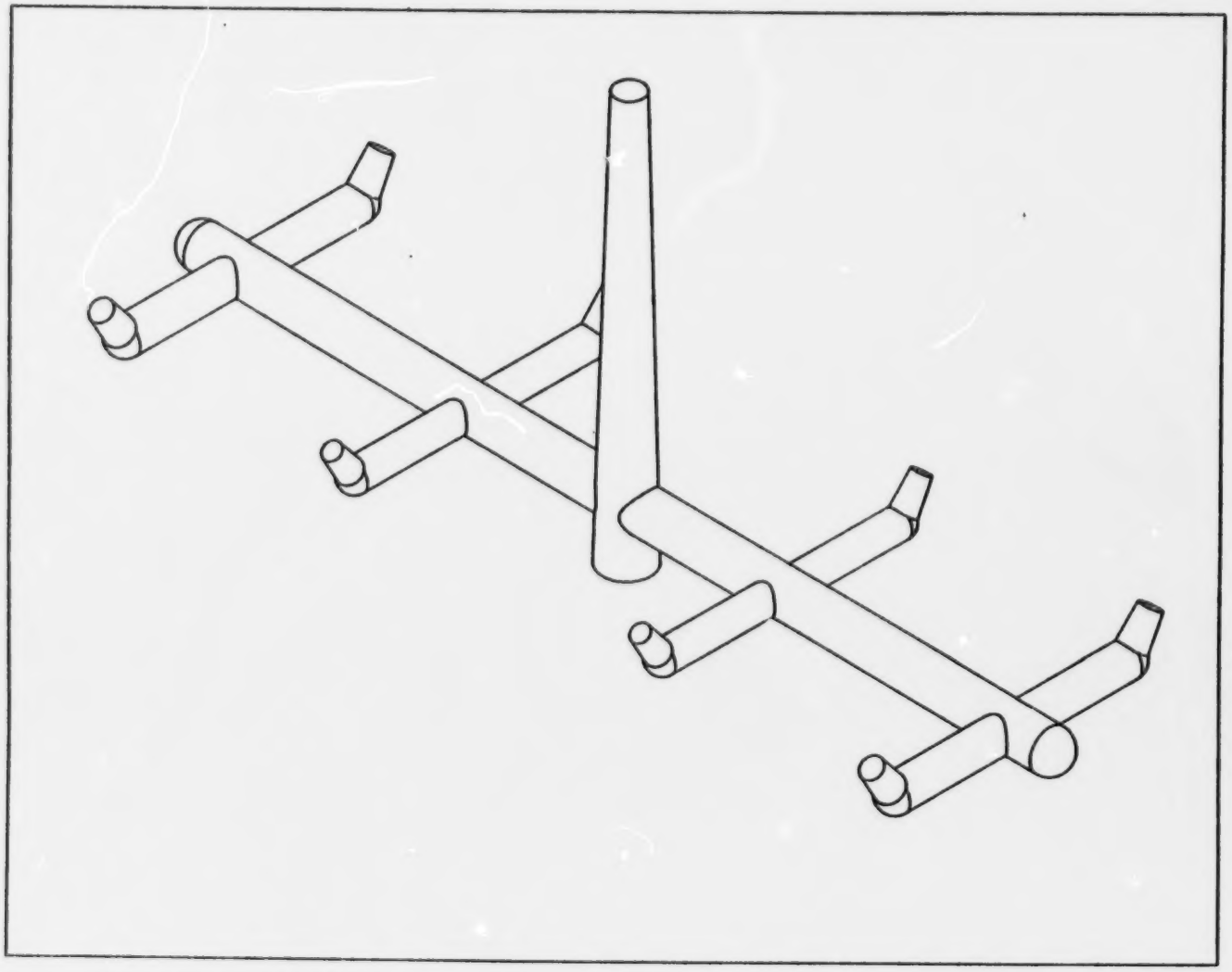


Figure 7, Application to the design of an eight cavity feeding system.

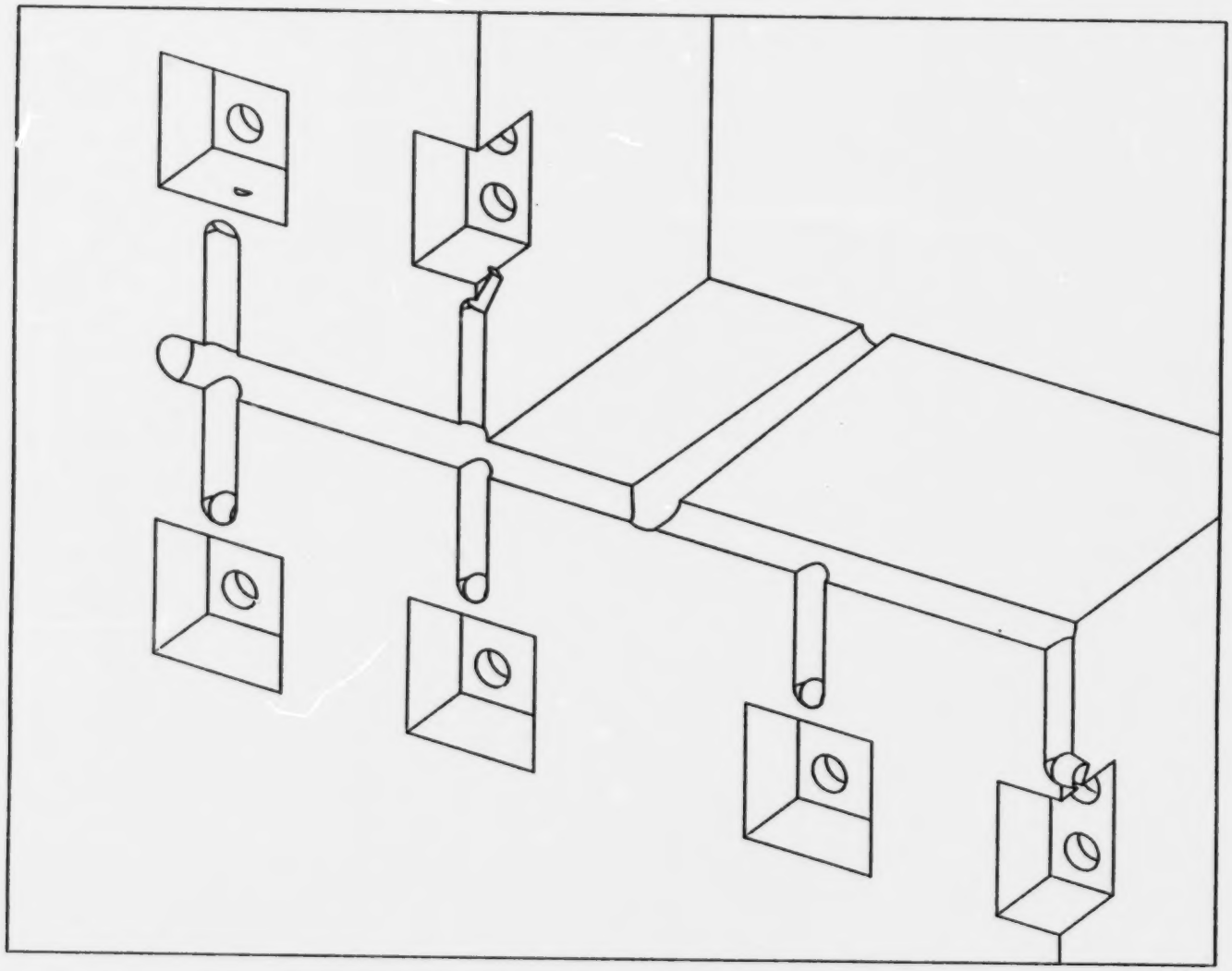


Figure 8, A cross section view of the cavity plate.

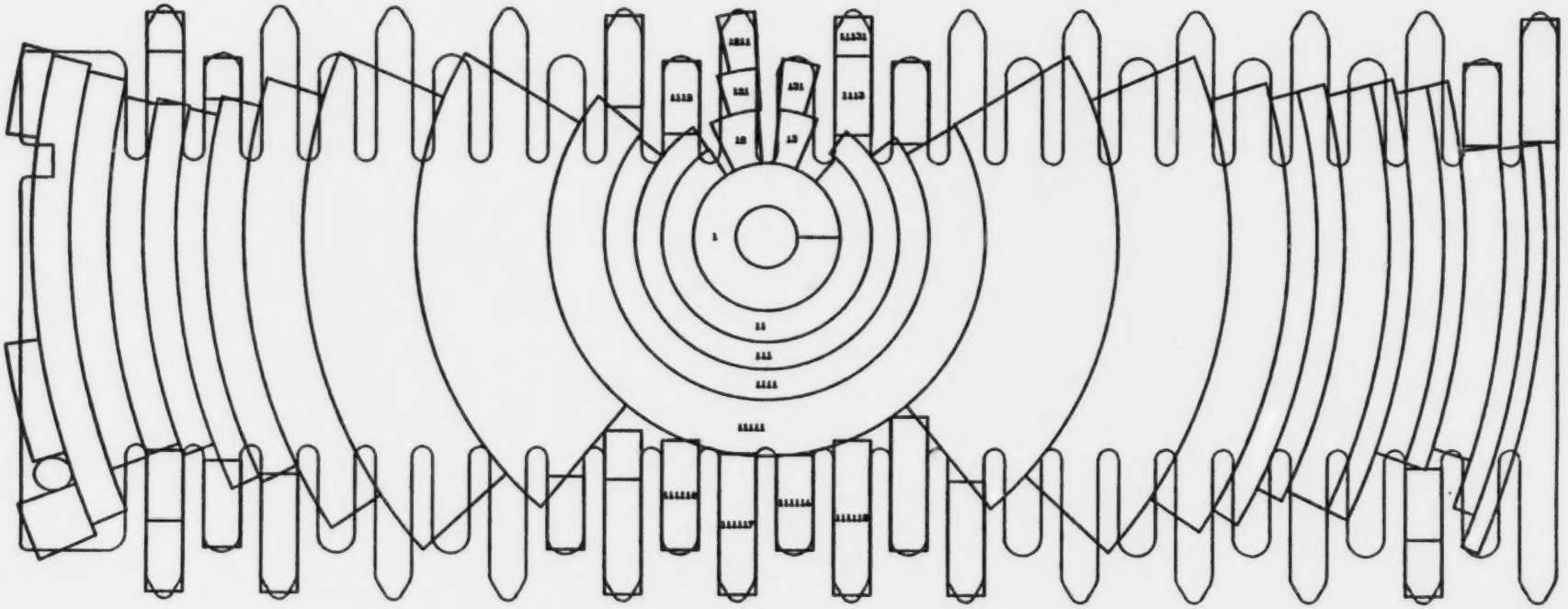


Fig. 9: Flow Pattern with Segmentation

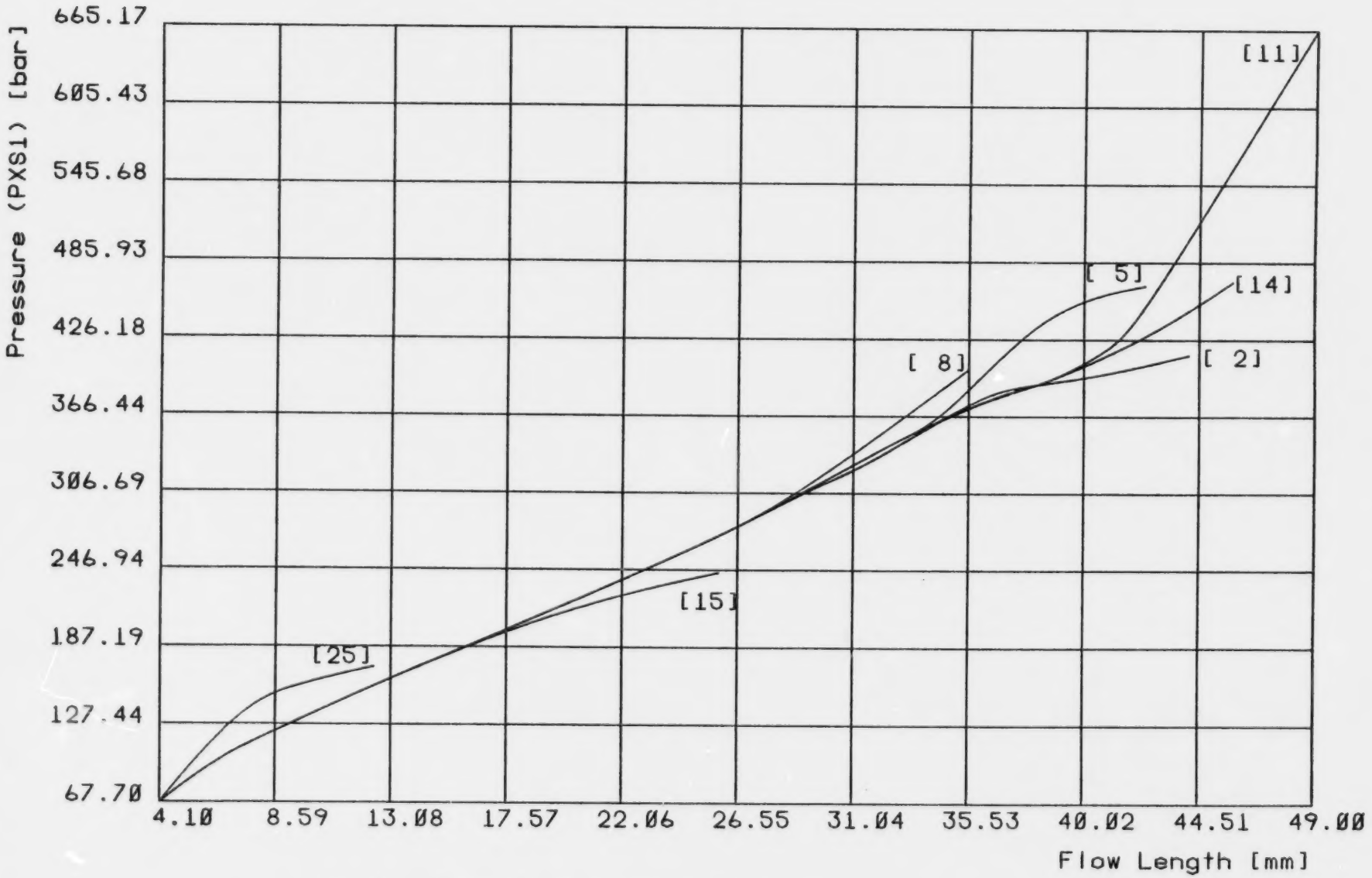
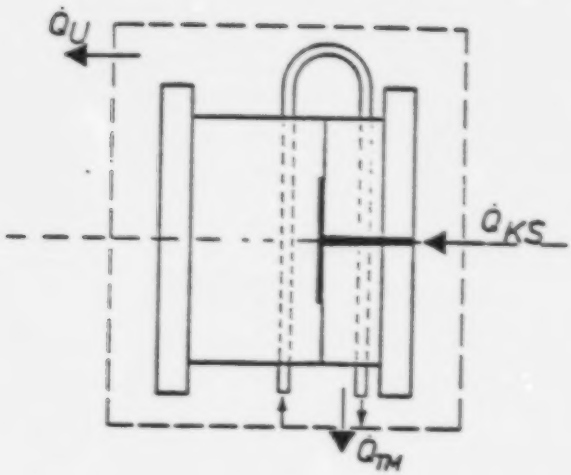


Fig. 10: Pressure variation against flow length




```
*
* HEAT FLOW BALANCE
*   ( + = SUPPLIED TO THE MOULDING )
*
*   PLASTIC MATERIAL          QKS :     592.976  (W)
*   SURROUNDING               QUM :    -142.966  (W)
*   CONVECTION                QKO :    -105.750  (W)
*   RADIATION                 QSTR:     -11.045  (W)
*   CONDUCTION                QLEI:     -26.171  (W)
*   ADDITIONAL                QZUS:       0.000  (W)
*   COOLING AGENT             QTM :    -225.005  (W)
*       ( per channel )
*   RATIO SURROUNDING/PLASTIC       QUM/QKS = CQ :   -24.1099 (%)
*
```

Fig. 11: Thermal Balance of Mould

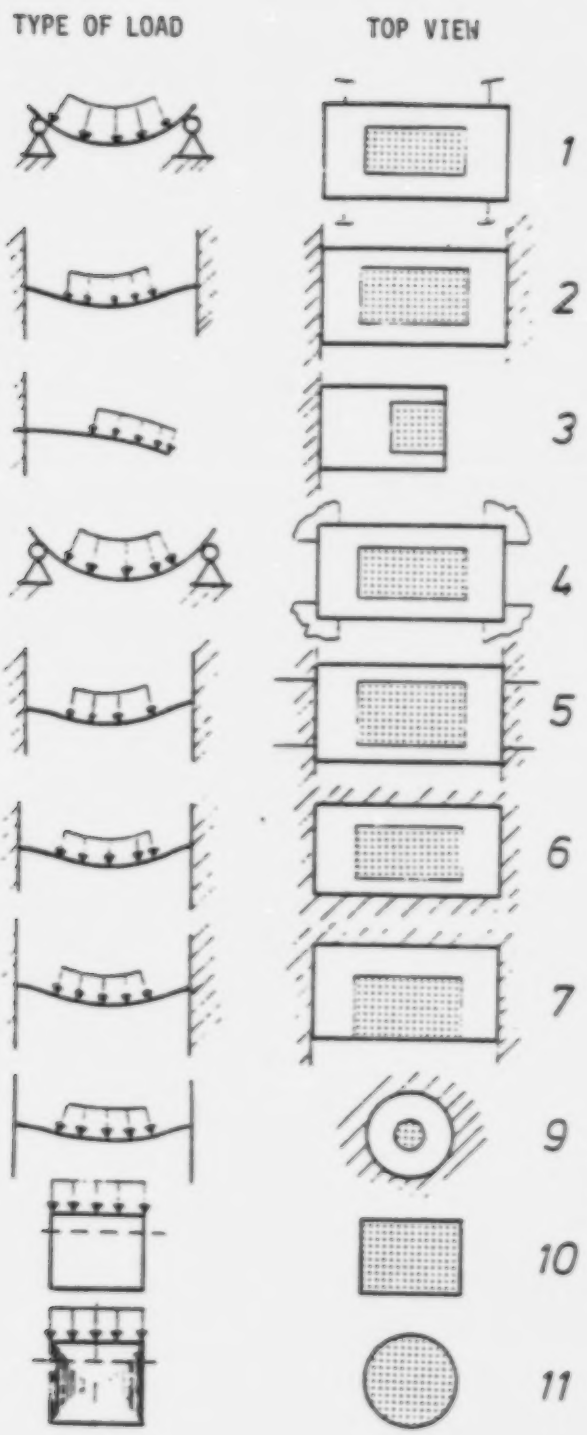


Fig. 12: Menu for Mechanical Analysis of moulds

SIMULATION OF MOULDING SHRINKAGE ON A CAD/CAM SYSTEM

SIMULATION DU RETRAIT AU MOULAGE SUR UN SYSTEME DE CFAO

by

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ENGLISH ABSTRACT

The prediction of shrinkage has always been a major problem for mould designers and moulders. The usual practice is to estimate shrinkage from data as published by the raw material suppliers or from past moulding experience. Since moulding shrinkage is not uniform in all directions this often led to many modifications of the cavity and core and occasionally to a complete retooling.

Melt flow analysis and mould cooling simulation using intrinsic material properties such as melt viscosity, heat capacity, etc, are presently available to end users. This article presents a computer assisted calculation of linear shrinkage using the results of these simulations such as pressure, temperature and cooling time.

RESUME FRANCAIS

La prédiction du retrait a toujours été un des problemes majeurs pour les moulistes et les transformateurs de l'industrie des matières plastiques. La méthode habituelle est d'estimer le retrait à partir des données des fournisseurs de résines. Comme le retrait au moulage n'est pas isotropique, ceci peut souvent imposer de nombreuses modifications du noyau et de l'empreinte et quelquefois nécessiter un réusinage complet du moule.

Les analyses de remplissage et du refroidissement utilisant les proprietes intrinsèques du materiau telles que la viscosité, chaleur spécifique, etc. sont de plus en plus utilisées par l'industrie. Cet article présente une methode de calcul du retrait assistée par ordinateur basée sur les résultats de ces analyses comme la pression, la température et le temps de refroidissement.

INTRODUCTION

The introduction of computer aided design and manufacturing is transforming the industrial world. For the thermoplastics moulding industry, the payoff is increased productivity, reduced scrap rates and a reduction in the amount of time rquired for debugging a new mould. In addition, the opening of new markets in very competitive fields requires, on the part of industry, an enhanced innovative attitude as well as products of superior quality.

This technological change necessitates profound transformations for Canadian industry from the shop floor equipment to the work habits of companies. The only method capable of resolving often contradictory requirements is the maximum integration of production.

The product design process entails many disciplines and call upon the empirical knowledge of many people. It is rare that a single designer will possess all of the knowledge required to produce a part. Our research goal consists of integrating the know-how of industry into a design system so that all users may have access to the required information.

The prediction of the shrinkage of an injection moulded part is a major problem during the design of the mould. Errors at this stage can cause considerable expense up to a completely new mould. This explains the interest that IPL has shown over the last three years in modelling shrinkage in plastic materials.

1 GENERAL DESIGN METHODOLOGY

Figure 1 summarizes the design stages for a part.

1.1 - Product Geometry

The designer starts by defining the dimensions of his product. He establishes the minimum tolerances, the required finish quality for the part and the normal conditions during use of the product.

1.2 - Properties of the Material

This module is essential in all analyses. The precision of the property values is essential to the validity of the results. Also contained in this module is the information required to determine the processing parameters for a given material. Usually, this data is supplied by the resin manufacturers.

1.3 - Processing Parameters

This module contains the materials processing parameters. These parameters can be used by the program to inform the user if the limits of the material are exceeded during a simulation.

1.4 - Preliminary Structural Analysis

A preliminary analysis by finite elements simulates the behaviour of a product under its operating conditions. The acceptability of the deformations of the structure and the level of stresses in the part are determined.

1.5 - Flow Simulation

The flow analysis is performed on the geometrical model based on the preliminary design of the product. The part is represented by primitives with simple forms (i.e. disks, plates and cylinders: Fig. 2). Particular primitives can be used to represent gates and runners. The software allows us to simulate the conditions during filling. The principal parameters calculated by the system are:

a) the injection time
b) the pressure drop
c) the material temperature
d) the shear rate of the material
e) the internal stress
f) the filling time for each element

1.6 - Simulation of the Cooling of the Part

The cooling simulation of a part is based on a thermal balance between the mould and the environment. This module calculates the minimum cooling time before demoulding and optimizes the cooling system.

1.7 - Moulding Conditions

After the preceding simulations, the operating conditions and the state of the material in the part are known.

The following results are calculated by the program:

a) the shear stress
b) the injection pressure
c) the temperature of the material
d) the temperature of the mould
e) the holding or packing pressure

f) the cooling time

1.8 - Evaluation of the Shrinkage

A this point, the calculation of the shrinkage of the part is done. The principal parameters that control the shrinkage are now known to the designer. The details of this stage are presented later in this paper.

1.9 - Dimensionning of the Mould

This module takes into account the results of the previous calculations so as to determine the required mould dimensions for the desired geometry. Compensation for the effects of shrinkage requires changes to the dimensions of the mould in three directions, but mainly in the directions parallel and perpendicular to the flow direction.

2. METHOD USED TO PREDICT THE SHRINKAGE

Many shrinkage studies were based on the P.V.T. (pressure, volume, temperature) diagram where the volumetric shrinkage of a part was determined. However, the practical application of this method is limited by the necessity of knowing the characteristics of the material at each point in the mould.

For example:

a) Determining the relation between the volumetric shrinkage and the linear shrinkage is very difficult.

b) The exact temperature of the melt in the mould during the injection cycle is difficult to predict.

c) During the solidification phase of the material, the variation in pressure is different for each point in the part. Consequently, this method requires the use of several pressure transducers in different positions in the mould.

A statistical approach avoids these problems. A mathematical model for the prediction of shrinkage is based on a multiple non-linear regression on the operating conditions of the injection press and on the geometry of the part. In addition, this method has the advantage of implicitly taking into account the conditions in the gate. Only one resin has been studied to date.

A large number of measurements were required to evaluate the precision of all of the parameters in the mathematical model. Once the general behaviour of the variations of these parameters is known, the mathematical model can be

generalized for other resins with a minimum of measurements.

This article presents the general models developped for a disk and a plate moulded with high density polyethylene. The final objective is to incorporate the prediction of shrinkage into a computer aided design system for injection moulding.

3. EXPERIMENTAL METHOD

3.1 Moulds

Four moulds with interchangeable cavities and a hot or cold runner system were used. For each of the cavities, a control system for the temperatures and injection pressures was installed.

1. Disk: 3.50 in. in diameter. Thicknesses 0.187, 0.125, 0.092, 0.062 in. Feeding system: hot runners.

2. Disk: 8.25 in. in diameter. Thicknesses 0.125, 0.092, 0.062 in. Feeding system: hot and cold runners.

3. Plate: 1*5 in. Thicknesses 0.187, 0.125, 0.092, 0.062 in. Feeding system: hot runners.

4. Plate: 3*10 in. Thicknesses 0.125, 0.092 in. Feeding system: hot runners.

5. Plate: 3*15 in. Thicknesses 0.125, 0.092 in. Feeding system: hot runners.

3.2 Injection Press

The characteristics of the injection press used for the test are as follows:

- 120 tons, with a process controller for the injection speed and the holding pressure. The shot size for the part was auto-correcting.

- A temperature control unit was added for the barrel and for the mould.

- A statistical control of the process was used to analyse the values of the variables studied (mean, standard variation, ...).

3.3 Material

A high density polyethylene was used. Its principal characteristics are:

1- Flow index = 7gr /10 min.
2- Density = 0.955 gr /cm **3.
3- Mean molecular weight = 70,000.

3.4 Parameters

After a few preliminary trials, the following moulding parameters were used in the analysis:

1. Holding or packing pressure
2. Cooling time
3. Mould temperature
4. Maximum injection pressure
5. Melt temperature

Tables 1 and 2 summarize a part of the tests that were performed.

3.5 Measurement of the Parts

The dimensions of a part continue to vary (shrink) after ejection from the mould. A graph of this variation versus logarithmic time is adequate for the representation of this phenomenon (Fig. 3). All specimens were measured 48 hours after moulding.

4. RESULTS AND DISCUSSION

We have found that the order of importance of the moulding parameters on shrinkage is the following:

The holding or packing pressure is the most important. This parameter can cause considerable increase or decrease in the shrinkage. Figure 4 shows the longitudinal shrinkage for a plate.

As indicated in figure 5, the thickness of the part is also very important for predicting the shrinkage.

The cooling time and the maximum injection pressure are equal in importance.

The melt temperature and the mould temperature are of secondary importance if the conventional limits of operation for a given material are respected (Fig. 6).

The mathematical models were developped from multiple non-linear regressions. For the present, these models apply only to disks and plates. For example, the following type of equation was used for the regressions:

$$S2 = A1 + A2 * HP + A2 * MET + A3 * TH + A4 * HP * COT + LE*(A5 + A6 * HP + A7 * MET + A8 * TH + A9 * INP + A10 * LE)$$

where:

- HP = holding pressure
- MET = melt temperature
- TH = thickness of the part
- COT = cooling time for the part
- INP = maximum injection pressure
- LE = flow length

The error between the predicted and measured shrinkage using this model is small. It should be noted that these models cannot adequately predict the shrinkage in the regions near the injection point. Typically, this includes all areas within 0.75 inches of the gate.

When moulded under the same conditions, the longitudinal shrinkage for a rectangular plate injected at one end is slightly greater than the radial shrinkage for a disk. This is caused by the greater orientation of the flow in a plate.

5.0 GENERAL METHOD FOR PREDICTING SHRINKAGE

The software presently available can determine the injection parameters: length of the moulding cycle, injection temperature and pressure, holding pressure and the design of the cooling circuit. However, these programs deal with the simulation of the melt flow, the cooling of the part and the in service performance (structural analysis). Few software packages are commercially available with the capability of linking the results of these simulations and the calculation of moulding shrinkages.

We are presently adding these mathematical models to an integrated system for injection moulding. The models developped for plates and disks can be generalized for more complex geometries. Figure 7 shows a bucket decomposed into primitive geometries (plates and disks). Starting with the shrinkage for each of the primitives and the geometrical constraints (cores and inserts), it is possible to calculate the resulting shrinkage at each point in the part.

These deformations caused by the shrinkage are then considered as displacements on the nodes placed on the boundaries of the primitives used during the analysis. These displacements correspond to forces generated in the part.

The presence of cores can be simulated by imposing a nul displacement on certain nodes. The solution of the apparent system of forces gives the resulting shrinkage of the part.

CONCLUSION

It is possible to predict the shrinkage of a part from its moulding parameters (holding pressure, injection pressure, mould temperature, melt temperature and cooling time) and its geometry. These parameters control the elastic recovery, the cooling time and the degree of cristallisation that are the basis of shrinkage and the formation of a surface layer during cooling.

HDPE MOLDING SHRINKAGE UNDER DIFFERENT OPERATING CONDITIONS

Thickness	VARIABLE	HOLDING PRESSURE (PSI)	MOLD TEMPERATURE (DEG. F)	MAX. INJECTION PRESSURE (PSI)	COOLING TIME (SEC)	MELT TEMPERATURE (DEG. F)
	RANGE	(8500-13000)	(60-120)	(10000-14000)	(7-17)	(390-500)
0.062	LENGTH	.029-.021	.025-.026	.026-.024	.026-.026	.024-.022
	WIDTH	.028-.022	.025-.026	.026-.025	.025-.026	.026-.025
basic conditions		(10000)	(90)	(11000)	(11)	(445)
	RANGE	(6000-12000)	(60-120)	(9000-14000)	(11-32)	(390-500)
0.092	LENGTH	.022-.018	.021-.020	.021-.019	.022-.019	.020-.019
	WIDTH	.027-.020	.023-.024	.023-.022	.023-.024	.024-.022
basic conditions		(9000)	(90)	(11000)	(21)	(450)

Table 1: Moulding conditions (shrinkages in inches/inch)

HDPE MOLDING SHRINKAGE UNDER DIFFERENT OPERATING CONDITIONS

Thickness	VARIABLE	HOLDING PRESSURE (PSI)	MOLD TEMPERATURE (DEG. F)	MAX. INJECTION PRESSURE (PSI)	COOLING TIME (SEC)	MELT TEMPERATURE (DEG. F)
	RANGE	(6000-12000)	(60-120)	(9000-14000)	(18-30)	(400-490)
0.125	LENGTH	.019-.016	.017-.019	.017-.016	.019-.016	.018-.017
	WIDTH	.022-.017	.018-.021	.020-.019	.019-.019	.020-.019
basic conditions		(9000)	(90)	(11500)	(24)	(445)
	RANGE	(7000-13000)	(50-110)	(10000-14000)	(28-44)	(390-480)
0.187	LENGTH	.020-.016	.015-.020	.018-.017	.020-.015	.017-.018
	WIDTH	.016-.012	.013-.016	.015-.014	.016-.014	.014-.015
basic conditions		(10000)	(80)	(12000)	(36)	(440)

Table 2: Moulding conditions (shrinkages in inches/inch)

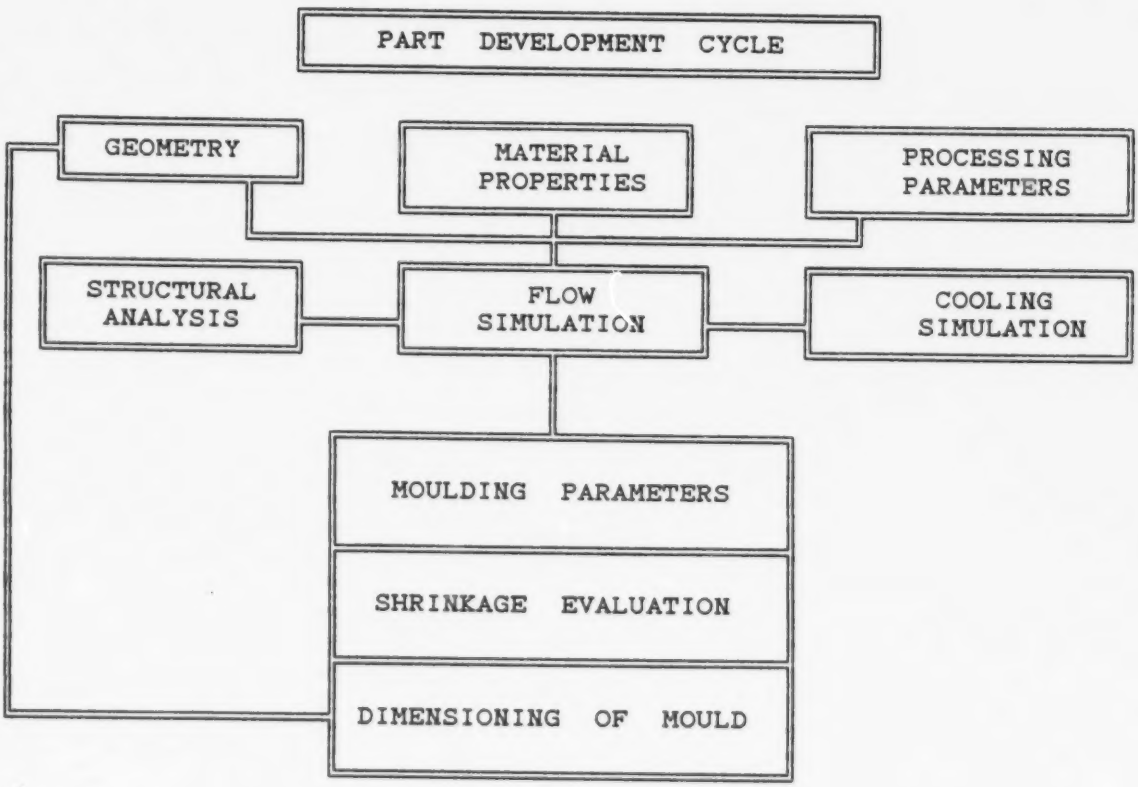

FIGURE 1: PART DEVELOPMENT CYCLE

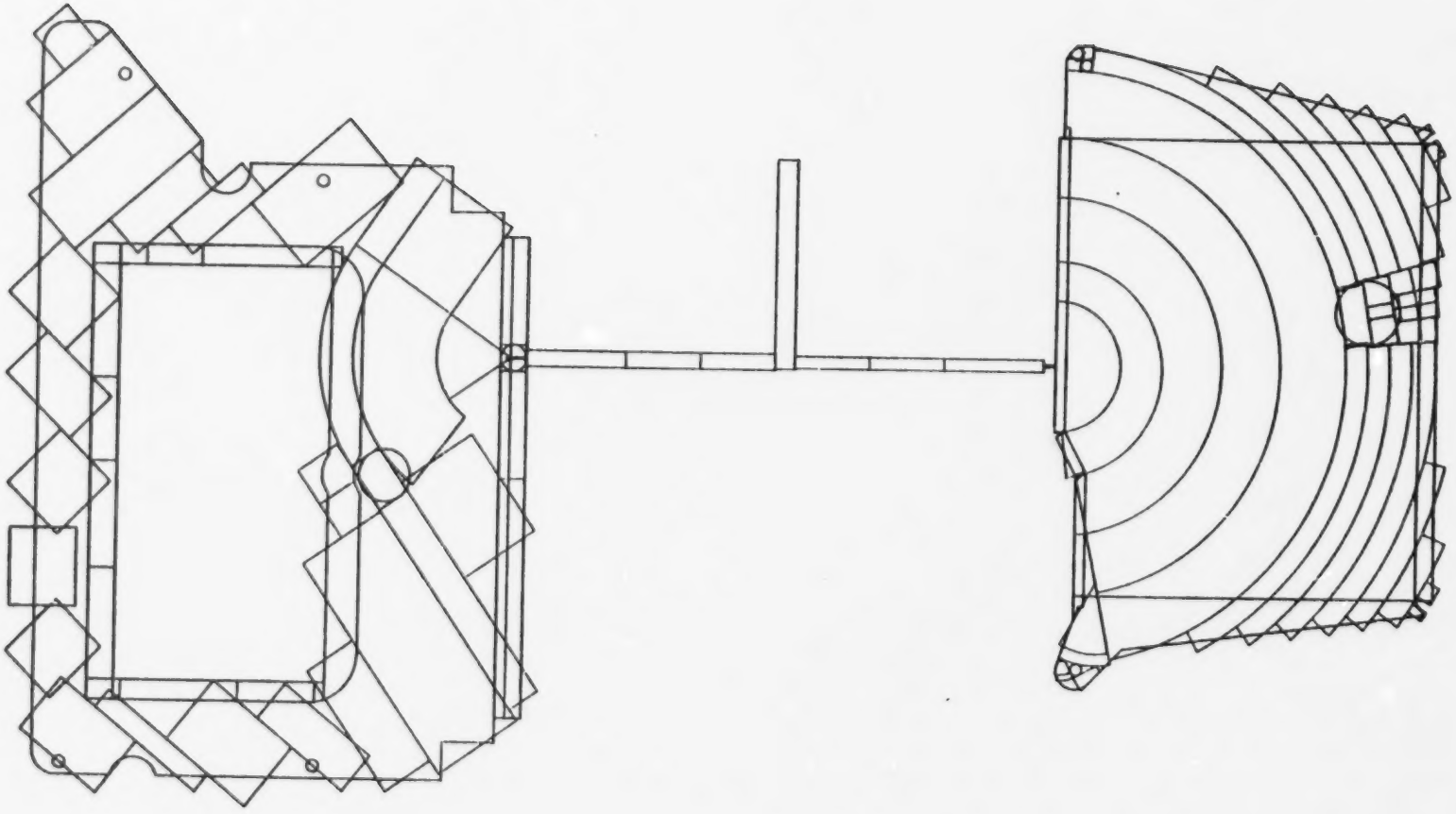

Figure 2: Segmentation in a two-cavity mould

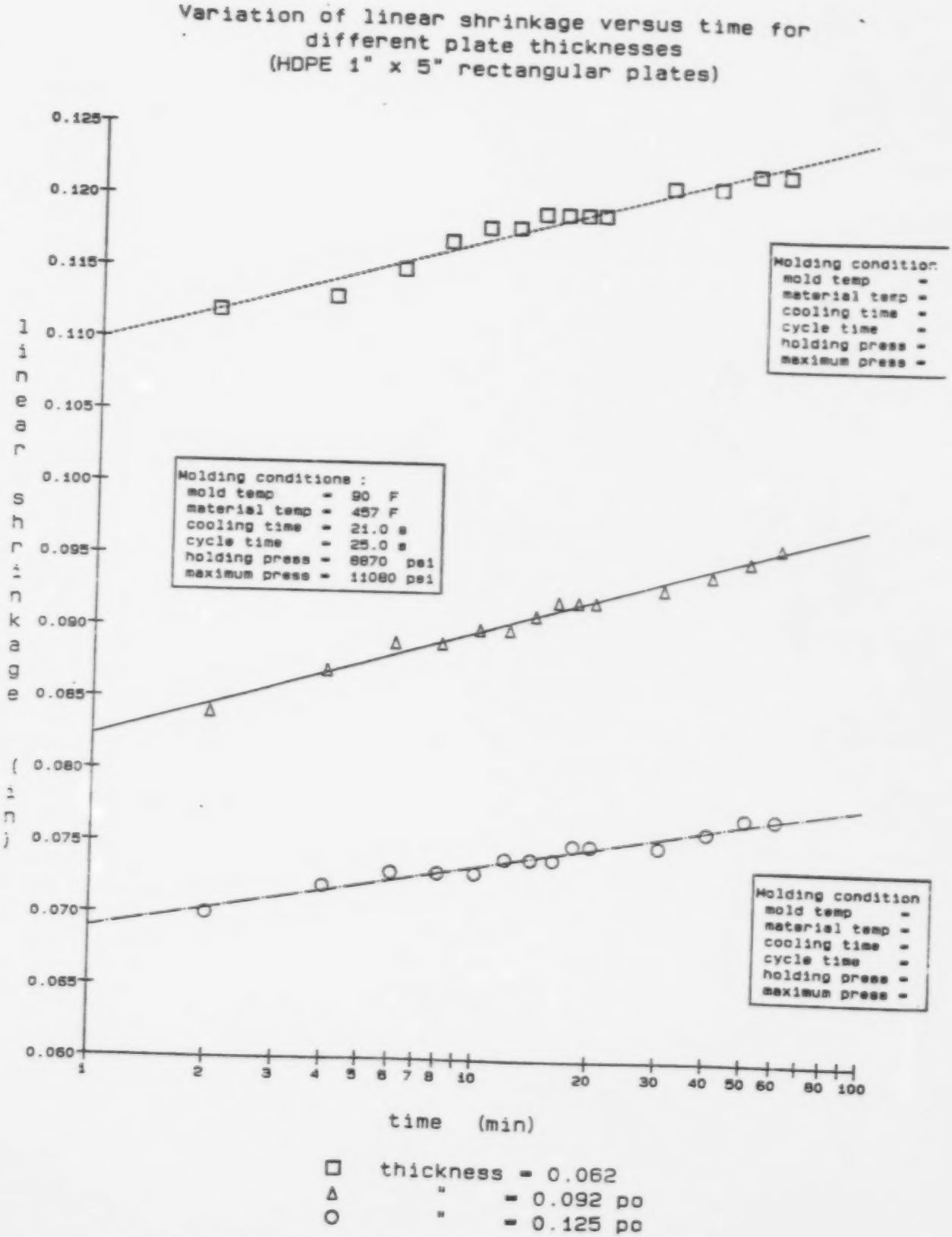

Figure 3: Variation of shrinkage versus time after demoulding

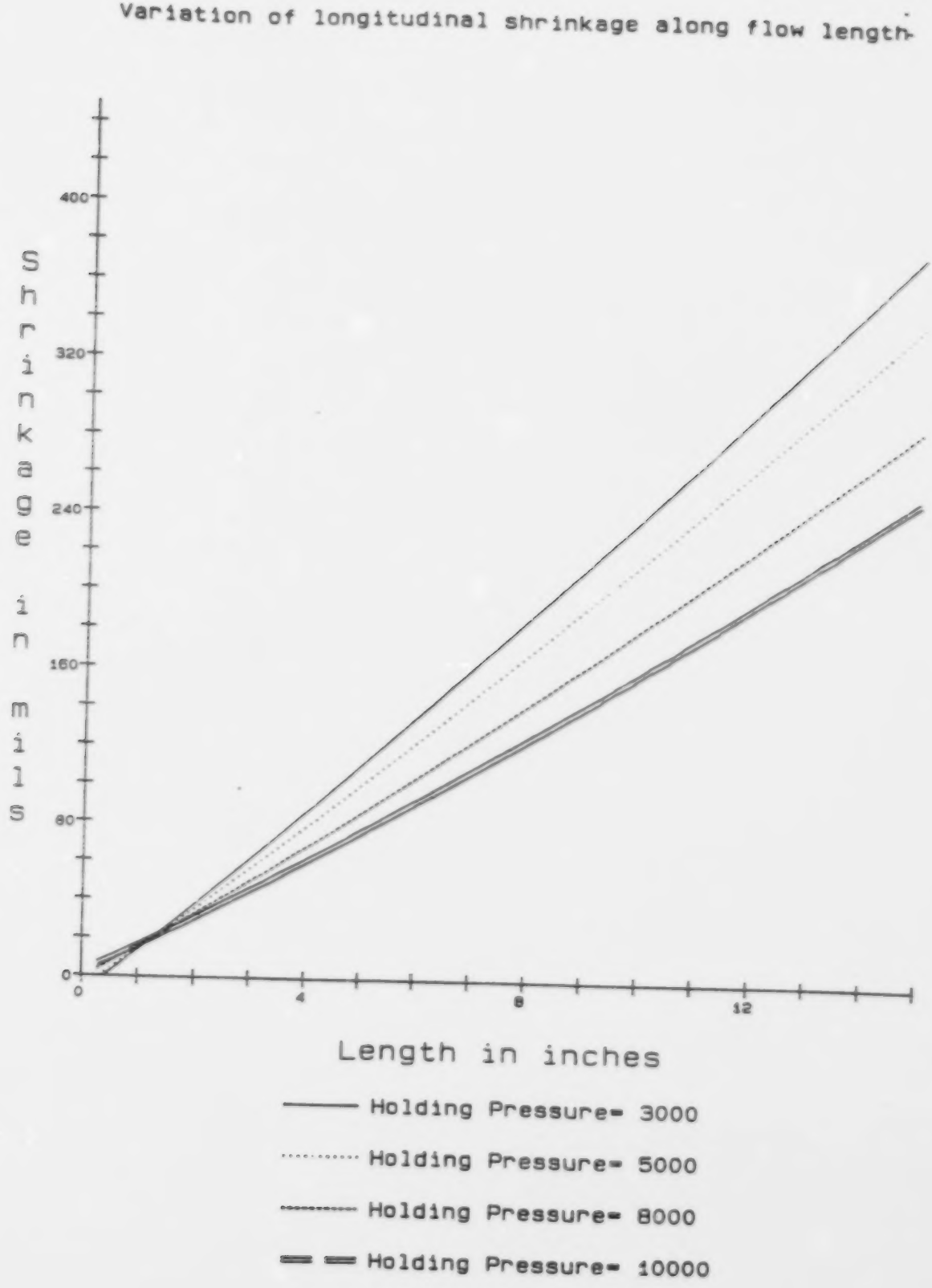

Figure 4: Longitudinal shrinkage of a plate versus holding pressure

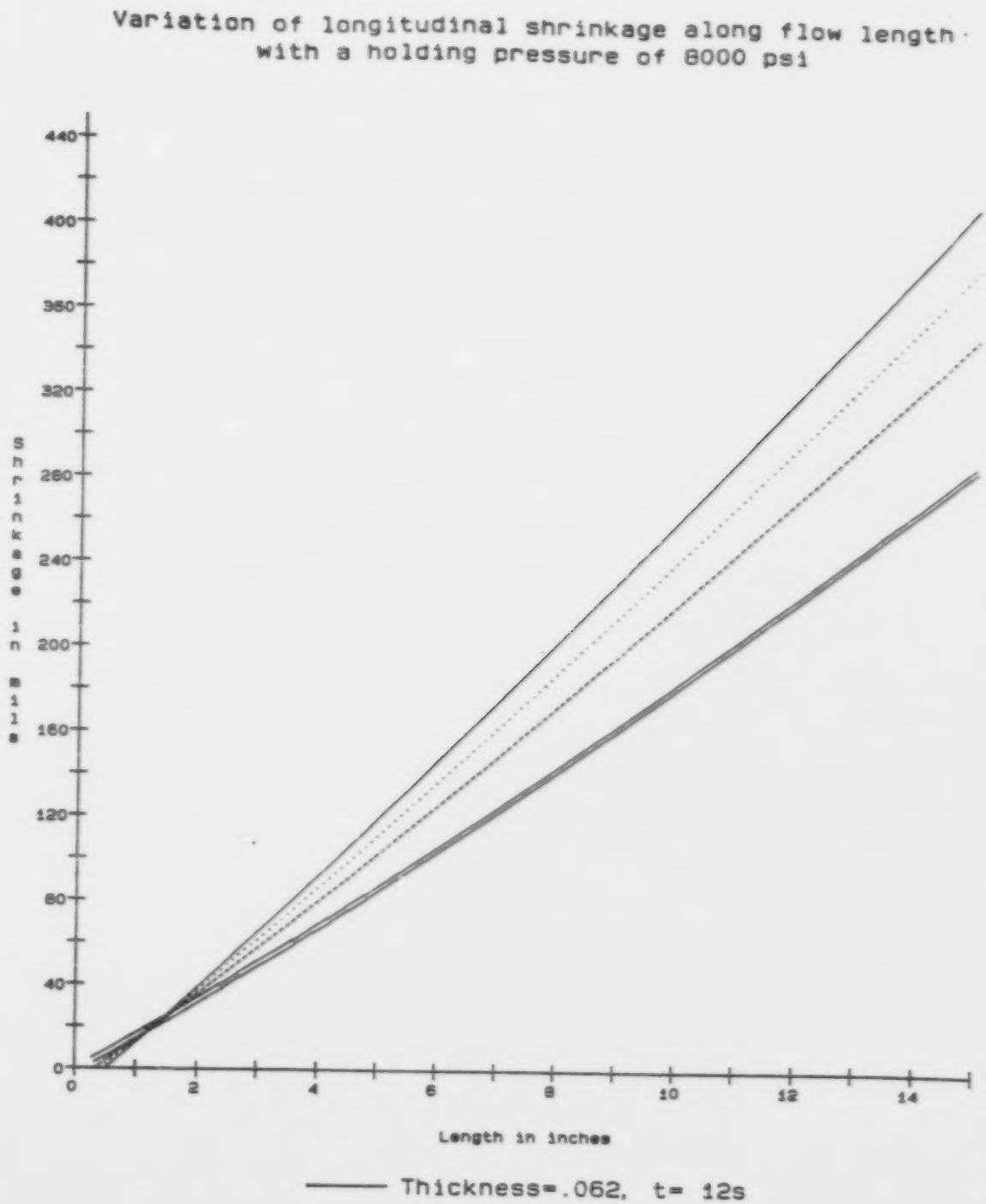

Figure 5: Longitudinal shrinkage versus thickness

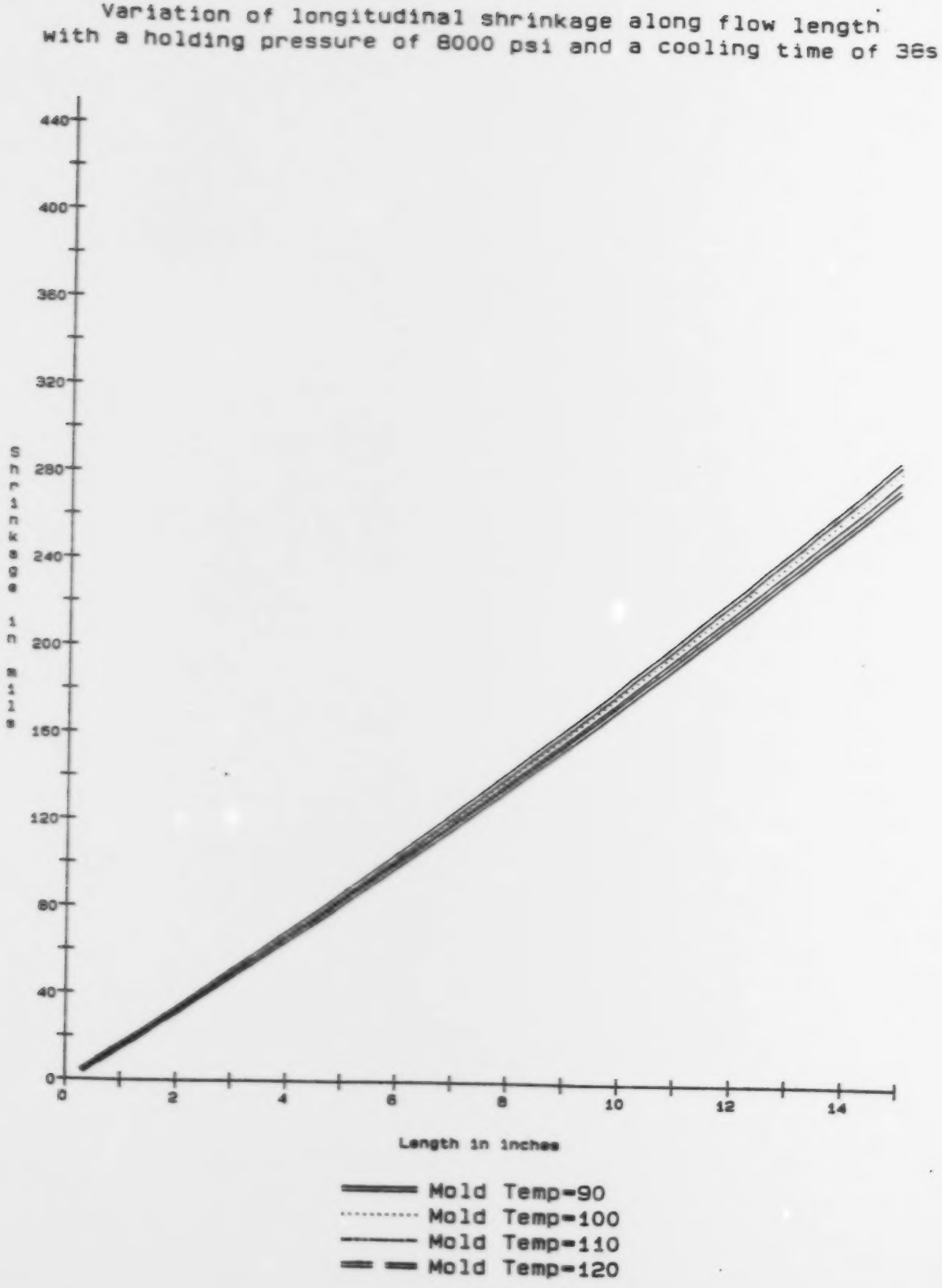

Figure 6: Longitudinal shrinkage versus mould temperature

A BUCKET DIVIDED INTO BASIC
GEOMETRIES: PLATES AND DISKS

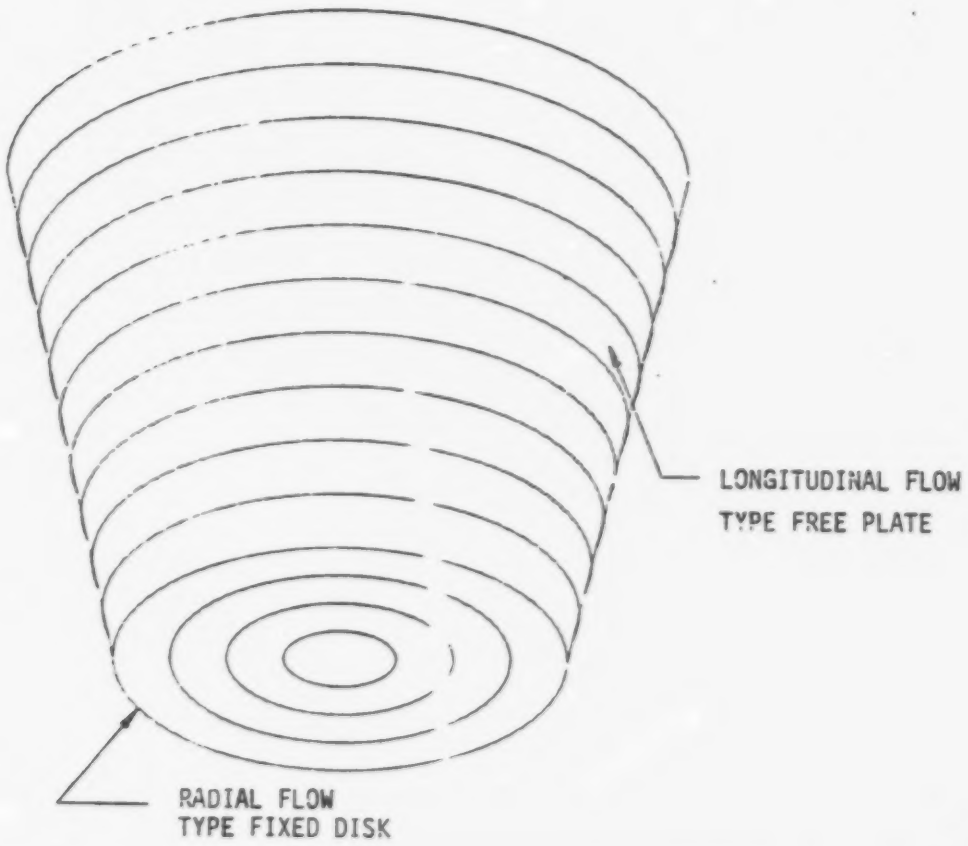

Figure 7: A bucket represented by two types of flow, fixed and free.

PROGRAMMABLE CONTROLLERS IN AN INTEGRATED MOULDING SYSTEM
LES CONTROLEURS PROGRAMMABLES DANS UN SYSTEME INTEGRE POUR LE MOULAGE

by

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ENGLISH ABSTRACT

After a brief description of an integrated system for moulding plastic parts, the emphasis will be placed on programmable controllers which represent the starting point of an integrated system. We will examine the present directions of the design of these controllers. The various functions of programmable controllers, such as the control of temperatures, pressures, displacements and times, will be discussed.

Following this, we will determine how the operating parameters required by the controller will be generated from the results of a mould simulation and from information databases of material properties, equipment characteristics and the geometry of the moulded part. This information will be transmitted to the programmable controller with the help of a microcomputer.

RESUME FRANCAIS

Après une description sommaire d'un système intégré pour le moulage de pièces plastiques, l'emphase sera mise sur les contrôleurs programmables qui représentent le point névralgique du système intégré. Nous examinerons les tendances actuelles dans la conception de ces contrôleurs. Les différentes fonctions des contrôleurs programmables, telles que le contrôle des températures, des pressions, des déplacements et des temps, seront discutées.

Par la suite, nous établirons comment les paramètres de fonctionnement requis par le contrôleur seront générés à partir des informations provenant de la simulation du remplissage du moule et des bases de données sur les propriétés des matériaux, les caractéristiques des équipements et les géométries des pièces moulées. Ces informations seront transmisent au contrôleur programmable de la presse d'injection avec l'aide d'un micro-ordinateur.

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1 INTRODUCTION

For several years, manufacturers of injection presses and control systems have invested a considerable effort in the creation of sophisticated programmable controllers. To illustrate the importance of this piece of equipment, we will describe it in relation to an integrated moulding system.

The development of programmable controllers is due to the large scale introduction of electronic microchips into injection machine controllers. The principal objective of a processor is the production of plastic parts of the highest possible quality at the lowest possible cost; this illustrates the importance of the programmable controller which oversees the injection machine.

2 LES PRINCIPAL COMPONENTS OF AN INTEGRATED MOULDING SYSTEM

Figure 1 illustrates a plant where the operations are under the control of a central computer which also perform the management of production. The principal functions are the automatic feeding of raw materials to various machines, the partial or total control of the machines by a programmable controller capable of communicating with the central computer and an automated handling system for the packing or the quality control inspection of the moulded parts. The moulding shop can be equipped with an automated change system for moulds and plasticating units, as well as an automated mould transport system between the shop floor and the mould warehouse. A computer aided engineering system, consisting of data bases containing useful information, such as material specifications or machine operating parameters, and a series of analysis programs for various phases of the injection cycle, such as cavity filling or mould cooling, can be added to this base structure.

The materials data base contains information that is directly usable by the analysis programs as well as other information related to the production machine operating parameters. For example, for a given material, we could find the recommended temperatures for the different zones of the barrel. The equipment data base contains the characteristics of the different presses, the auxiliary equipment, including their limitations. The mould and part data base contains all of their geometrical and mechanical characteristics. The majority of injection machine operating parameters will be specified by the information contained in these three data bases.

The analysis programs for the various phases of the injection cycle are the most complex software modules in the system. Workers in numerous research centers and universities are striving to improve the mathematical models used by the analysis programs. Several analysis and simulation programs for the mould cavity filling phase and the mould cooling phase are already available.

Presently, analysis programs for the mould packing phase that will predict the optimal holding pressure profile for a given part are under development in several laboratories. Following this overview of the aids available for the design of moulds, a closer examination of programmable contollers and their role in an integrated moulding system will be carried out.

3 THE PRINCIPAL TYPES OF PROGRAMMABLE CONTROLLERS FOR INJECTION MOULDING

Figure 2 illustrates the diferent types of programmable controllers that can be connected to an injection press. Also note that the actions taken by the different types of programmable controllers is coordinated by a micro-computer. This micro-computer can coordinate several injection presses simultaneously, depending on its capabilities.

We will describe the basic components of programmable controllers, using, as an example, the supervision of the moulding parameters of an injection machine. Three types of control algorithms are available for this case.

First, there is open loop control (fig. 3), which is the simplest of the control algorithms. A given setpoint, which corresponds to an input signal of a specific value, is used to modify a process variable. However, external perturbations, (for example, a change in the temperature or the humidity of the ambiant air) can cause fluctuations or deviations in the output signal. In this case, no correction is applied to the input signal. In programmable controllers, all parameters that are relatively immune to external perturbations can be controlled with open loops. For example, the control of elapsed times in an injection cycle and the majority of safety systems operate with open loop controls.

The second type of control uses a closed loop (fig. 4). In this case, a given setpoint must correspond to a certain output signal. If this output signal varies from its desired value, then the error, which is the difference between the actual and desired values, is analysed by a correction transfer function and used to adjust the input signal so that the output signal returns to the desired value. The correction transfert function describes the relationship between the input and output signals; usually, this function is determined experimentally. An increasing number of parameters, particularly those with a direct influence on the quality of the moulded part, are controlled with closed loops. For example, the speeds and pressures on the screw as well as the temperatures of the barrel are controlled with closed loops.

The third type of control is called adaptive control (fig. 5). In this case, there are two loops in series, each with different response times, influencing the same parameter. The first loop is a standard control loop,

either open or closed. The second control loop, which is a closed loop, has an output signal which corresponds to the input signal of the first loop. This type of regulation is used most often for the optimal control of a process where certain parameters or perturbations can not be controlled directly. Again, adaptive control is used on parameters with a direct influence on the quality of the moulded part; for example, a pressure profile in the mould or the temperature of the melt.

Adaptive control is most often used on injection presses to regulate the amount of material to be plasticated, i.e. the shot size. In the first loop, the setpoint is the desired amount of resin (or cushion) that remains in the barrel at the end of the injection phase. The input signal of the first loop, which corresponds to the position of the screw at the beginning of the injection phase, is compared to a value read by a displacement transducer. The input signal of the second loop is the actual final position of the screw at the end of the injection phase, which is read by the same displacement transducer. The difference between the actual final position of the screw and the desired final position of the screw (based on the desired cushion value) is used to calculate a correction to the position of the screw at the beginning of the injection phase, i.e. the input signal of the first loop.

4 THE STATE OF PROGRAMMABLE CONTROLLER TECHNOLOGY AND FUTURE TRENDS

Ideally, programmable controllers should be able to regulate all of the parameters of an injection press. This represents over forty parameters.

Although some programmable controllers only use open loop controls, most are based on both open and closed loop regulation while some also use adaptive control. Since it is difficult to disassociate the programmable controller from the injection machine, the discussion will be based on the control parameters of a press.

The three most important parameters, whose controls have evolved the most rapidly, are the injection speed, the holding (or packing) pressure and the back pressure during plastication. These were the first parameters to be controlled with closed loops. The injection speed is specified as a speed profile as a function of several discrete increments of screw position with linear interpolation between the increments. For the holding and back pressures, a holding pressure profile as a function of time and a back pressure as a function of the screw position, again with several discrete increments and lineer interpolation between the increments, are used. The actuator for these parameters is usually a servo valve; this device gives the best control of the hydraulic flow rates and pressures.

The transition from an injection speed profil to a holding pressure profile at the end of the injection phase can be based on three different conditions: a screw position, a hydraulic pressure (behind the screw) and a mould cavity pressure. Typically, all three modes are used simultaneously, with one of the conditions specified (e.g. the mould cavity pressure) so as to occur before the others. The other two conditions act as safeties, by adjusting their setpoints to values somewhat above their actual values at the transition point. The different screw positions are usually regulated with closed loop controls.

A hydraulic motor rotates the screw during plastication; hydraulic motors are more flexible than electric motors in as much as control of speed and applied torque are concerned. Open loop regulation is generally used, however, some controllers now employ closed loops to control the screw rotation. The availability of plastication simulation software will spur the implementation of closed loop control of the screw rotation.

For barrel temperatures, newer programmable controllers use closed loop regulation whose correction transfert functions are automatically determined when the injection machine is cold started. In addition, the initial heating rates used from a cold start are limited so as to eliminate any excessive thermally induced mechanical loads on the equipment. In the future, adaptive controls may be used for temperature regulation, where the input signals are the melt temperature or viscocity. The same tendencies are observed for the control of the mould temperatures.

The last of the important parameters for a high quality moulded part is the mould clamping pressure. Usually regulated with an open loop, newer programmable controllers are tending towards closed loop regulation, which permits a reduction in the clamping pressures used, leading to a reduction of energy consumption and a reduction of the loads and deformations imposed on the mould.

There are many more parameters that regulate an injection press, however, they have less important influences on the quality of the moulded parts. For this reason, they will not be exhaustively described. Nevertheless, certain of these parameters have considerable influence on the total cycle time; for example, the speeds and distances of the opening and closing of the mould and of the advance and backup of the plasticating unit. Therefore, they are often regulated with closed loop controls, so as to permit an improved optimization of these parameters.

The remaining parameters are generally regulate with open loops; for example, limit positions, elapsed times, safety pressures and limit temperatures. For maximum flexibility, a programmable controller should regulate all of these parameters. However, many of these adjustments, such as the limit positions, are manually adjusted on the injection machine itself.

Consequently, certain manual operations must be performed when changing the mould even if the press is equipped wivh a programmable controller.

Some controllers are equipped with bad part detection systems that facilitate quality control. The programmable controller verifies that a certain parameter that greatly affects part quality, for example, the mould cavity pressure profile or the injection hydraulic pressure profile, remains within specified tolerances. If the parameter wanders beyond its tolerances, the part is declared bad and separated from the good parts.

Similarly, safety limits can be specified for certain parameters that greatly affects part quality. If these safety limits are passed, then the programmable controller stops the injection machine. When human supervision of the process is minimized, the programmable controller must have the capability of detecting such problems and stopping the press, so as to avoid an entirely defective production run or even damage to the equipment.

5 COMMUNICATION WITH PROGRAMMABLE CONTROLLERS

Once the press is entirely controlled, a group of setpoints can be transmitted to the programmable controller. How these setpoints are generated and where they come from are the next questions. The set-up of an injection machine for a new production run is done in two stages.

The first stage is an initial sut-up of the press so as to mould the first parts, but with a long cycle time. The objective is to verify that the mould is operating as expected and to observe the quality of the first parts. Table 1 is a non-exhaustive example of an approach that can be used to determine the initial set-up parameters. This approach is based on two types of information.

The first type of information comes directly from the various data bases related to the materials and equipment or from the results of the different simulation programs available in an inetgrated system. The second type of information comes from various rules that are typically empirical and are based on the collective experience of the machine operators and set-up technicians (rules of thumb). The enormous advantage of this approach is its ability to evolve and adapt to different conditions as the company gains more experience. The data bases become richer, because when certain information is lacking, it can be found by various means and can be easily added to the existing information. The performance and ease of use of the various simulation and analysis programs are also increasing with time. Finally, rules expressed in such a fashion can be more easily questionned and analysed, so as to become more efficient and complete.

To illustrate this stage, we shall use as an example the generation of an injection speed profile that is to be transmitted to a programmable controller for the initial set-up of the injection machine. The mould has been designed on a CAD system. All of the information related to the mould, injection press and material is known. Assuming that a constant flow front velocity is desired during the filling of the mould cavity, we can determine with a good precision the melt flow rate required at each moment during the filling phase, since the geometry of the cavity and the characteristics of the melt are known. From there, by taking into consideration the geometrical characteristics of the press, the injection speed profile required for the desired variable melt flow rate can be determined. Depending on the controller, the profile can be segmented into five or ten discrete values. These values can then be transmitted from the computer which does the calculations to the programmable controller via a micro-computer.

The second stage consists of optimizing the injection machine set-up for the subsequent and future production runs. The objective here is to produce the best possible moulded parts in the shortest possible cycle times. Table 2 shows the approach that can be used to determine the optimized set-up. The approach is very similar to that used in the initial set-up. The principal difference resides in the rules used to optimize the process. This approach will probably permit the development of new adaptive controls of process variables that have not been exploited due to the lack of sufficiently powerful tools.

6 CONCLUSION

The proposed approach establishes the types of information that should be transmitted between a CAD/CAM system and a programmable controller on an injection machine. The implementation of such a system will results in unsuspected improvements. The plastics processor will possess a powerful tool that will improve his understanding of the processing of polymeric materials, leading to a reduction in scrap rates and to an improved optimization of the set-up parameters of an injection press.

In addition, the approach proposed here can be utilized with other methods of processing polymeric materials, such as blow moulding, compression moulding and reaction injection moulding.

TABLE 1: SOURCES AND RULES FOR THE INITIAL SET-UP PARAMETERS ON A PROGRAMMABLE CONTROLLER ON INJECTION PRESS

INJECTOR CONTROL

PARAMETERS	SOURCE	RULE
INJECTION SPEED PROFILE	M.S.DB. M.F.SIM. E.DB.	CONDITION: Shear rate in the mold must not exceed material specifications VALUE: Based on maximum shear rate calculated inside the mold REASON: No resin degradation
INJECTION PRESSURE PROFILE	E.DB.	CONDITION: None VALUE: High REASON: Sufficient pressure for injection speed requirements

ABBREVIATIONS:

M/C	Machine
E.DB.	Equipment DataBase (Injection M/C, mold, part, auxiliary equipment)
M.P.DB.	Mold and Part DataBase
M.S.DB.	Material Specifications DataBase (Resin manufacturer)
M.F.SIM.	Mould Filling SIMulation (Variety of software already available)
COO.SIM.	Cooling SIMulation (Variety of software already available)
PA.SIM.	PAcking SIMulation (Software available at some future date)
PL.SIM.	PLastication SIMulation (Software available at some future date)

CLAMP CONTROL

PARAMETERS	SOURCE	RULE
DAYLIGHT DISTANCE BETWEEN MOLD HALVES	E.DB. M.P.DB.	CONDITION: None VALUE: Twice the part and sprue depths + 10% for safety REASON: Part ejection
CLAMPING FORCE	M.F.SIM. E.DB. M.P.DB.	CONDITION: VALUE within the M/C capabilities VALUE: (Projected area * peak cavity pressure) + 10% for safety REASON: Prevent flashing at the mold parting line
MOLD OPEN AND CLOSE SPEED PROFILE	E.DB.	CONDITION: None VALUE: Extremely low REASON: So that no damage to the mold occurs

TABLE 2: SOURCES AND RULES FOR THE OPTIMIZED SET-UP PARAMETERS ON A PROGRAMMABLE CONTROLLER FOR AN INJECTION PRESS

INJECTOR CONTROL

PARAMETERS	SOURCE	RULE
INJECTION PRESSURE PROFILE	E.DB.	CONDITION: After at least 20 moulding cycles VALUE: 5% higher than the average profile from the previous 20 moulding cycles REASON: A significant deviation from the profile can cause bad parts

ABBREVIATIONS:

M/C	Machine
E.DB.	Equipment DataBase (Injection M/C, mold, part, auxiliary equipment)
M.P.DB.	Mold and Part DataBase
M.S.DB.	Material Specifications DataBase (Resin manufacturer)
M.F.SIM.	Mould Filling SIMulation (Variety of software already available)
COO.SIM.	Cooling SIMulation (Variety of software already available)
PA.SIM.	PAcking SIMulation (Software available at some future date)
PL.SIM.	PLastication SIMulation (Software available at some future date)

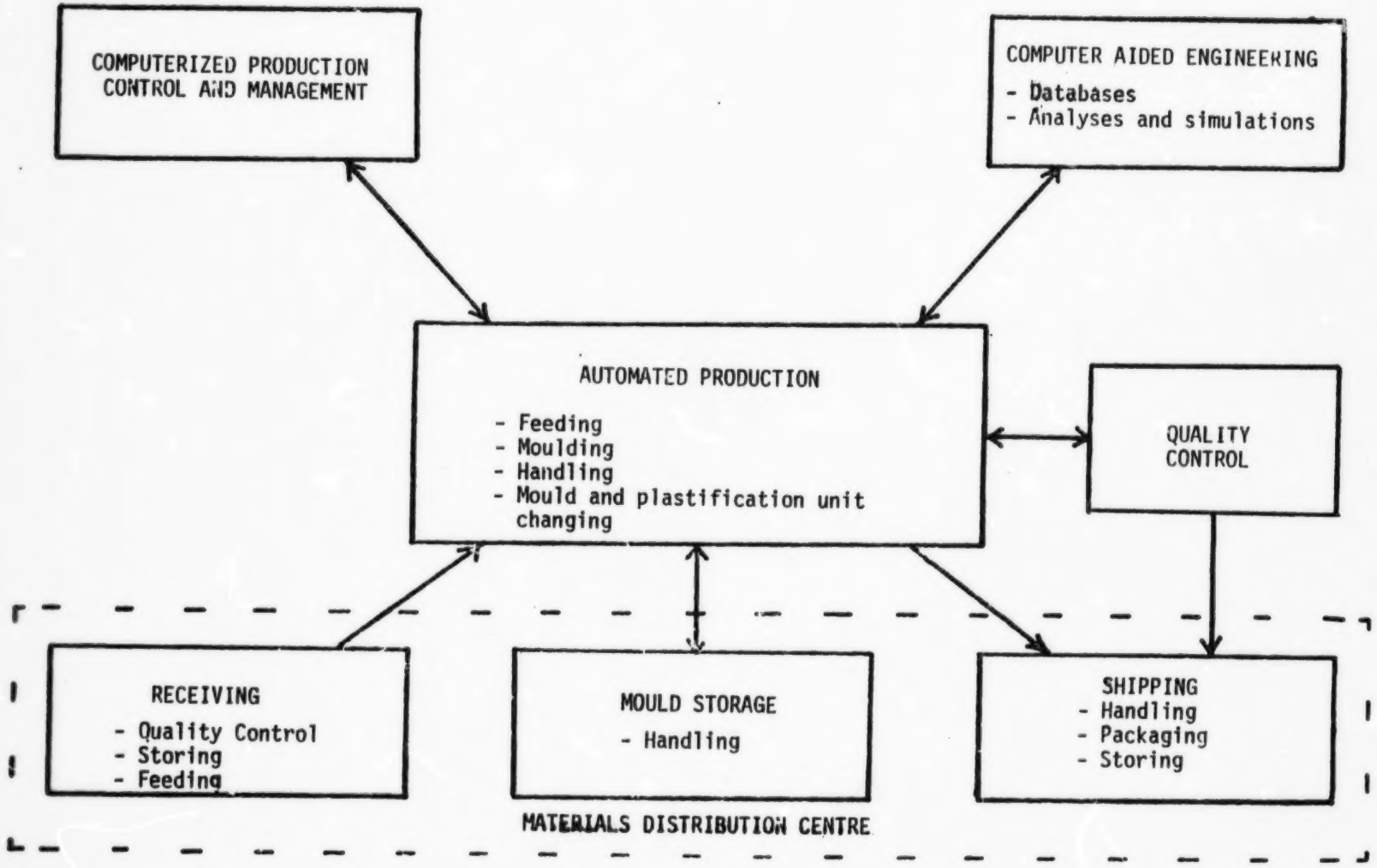

Fig. 1: THE PRINCIPAL ELEMENTS OF AN INTEGRATED MOULDING SYSTEM

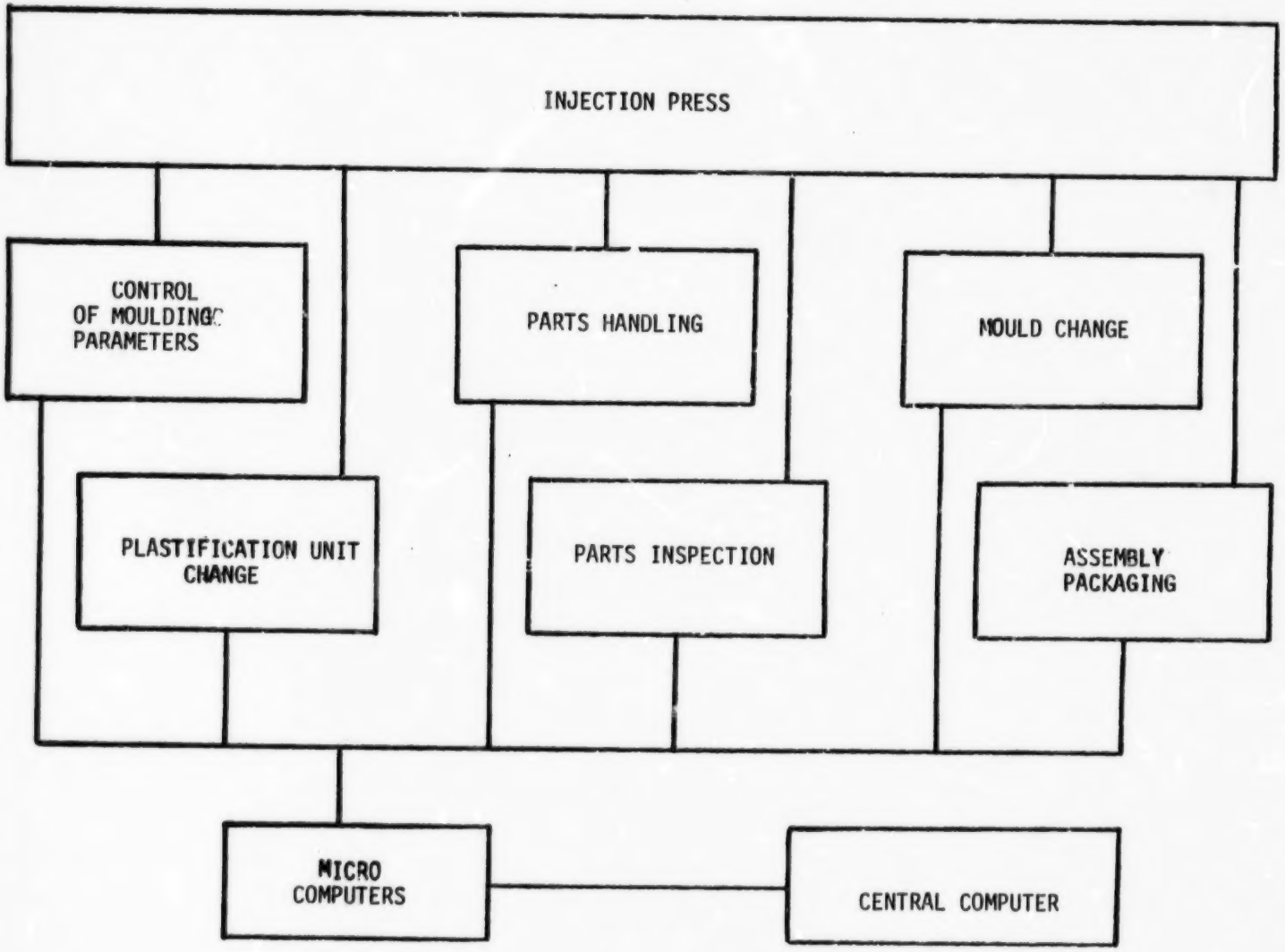

Fig. 2: Types of programmable controllers for moulding

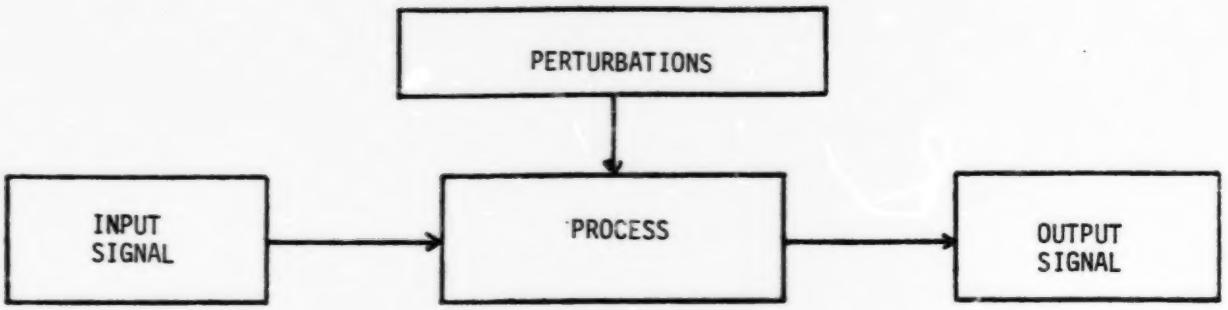

Fig. 3: OPEN LOOP (INTRACYCLE)

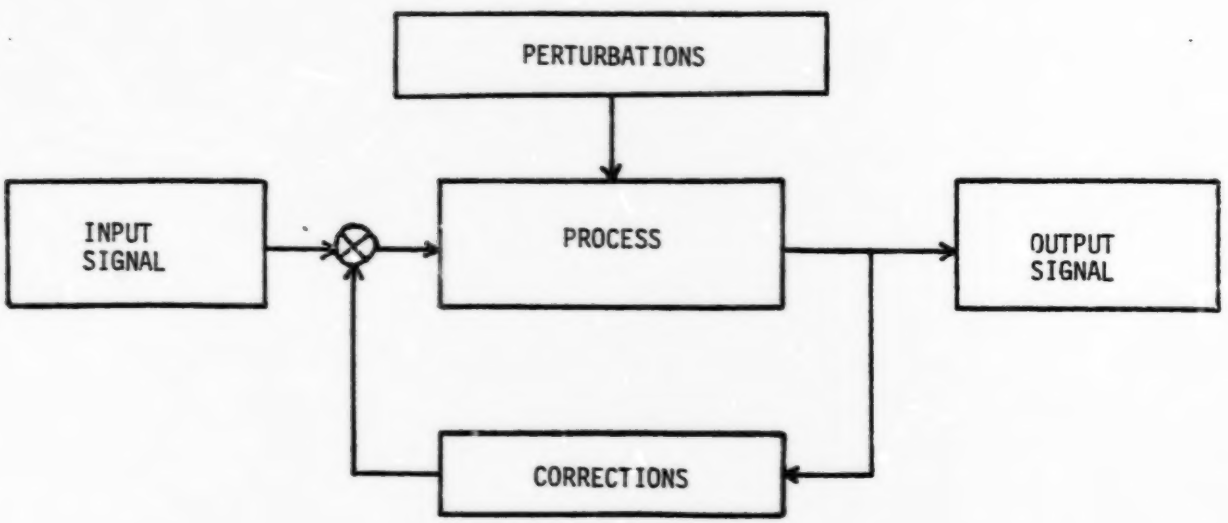

Fig. 4: CLOSED LOOP (INTRACYCLE)

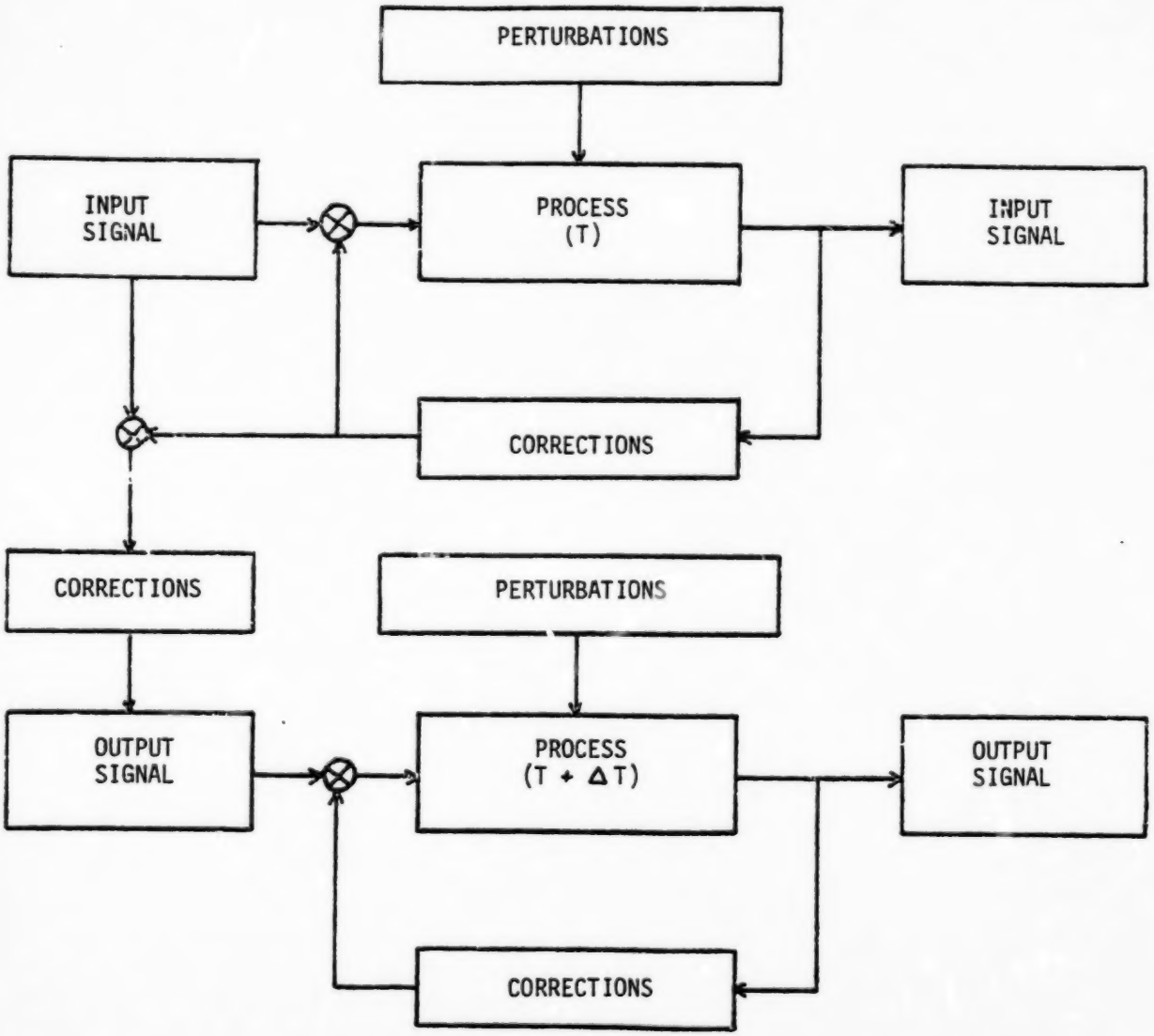

Fig. 5: ADAPTIVE CONTROL (INTERCYCLE)